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Land Disposal of Hazardous Waste Proceedings of the Annual Research Symposium (9th) Held at Ft. Mitchell Kentucky on May 2-4, 1983

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16. ABSTRACT

The Ninth Annual Research Symposium on Land Disposal, Incineration, and Treatment of Hazardous Wastes was held in Ft. Mitchell, Kentucky, May 2, 3 and 4, 1983. The purposes of the Symposium were (1) to provide a forum for a state-of-the-art review and discussion of ongoing and recently completed research projects dealing with land disposal, incineration, and treatment of hazardous wastes; (2) to bring together people concerned with hazardous waste management who can benefit from an exchange of ideas and information; and (3) to provide an arena for the peer review of the Solid and Hazardous Waste Research Division's and the Industrial Pollution Control Division's research programs in hazardous waste management. These Proceedings are a compilation of papers presented by the symposium speakers.

The symposium proceedings are being published as two separate documents. In this document, Land Disposal of Hazardous Waste, seven technical areas are covered. They are as follows: (1) Land Disposal Research Overviews, (2) Landfill Design and Operation, (3) Pollutant Movement, (4) Pollutant Control-Liners, (5) Waste Modification, (6) Cost/Economics, and (7) Remedial Action.

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OFFICE OF RESEARCH AND DEVELOPMENT
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CINCINNATI, OHIO 45268

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These Proceedings have been reviewed in accordance with the U.S. Environmental Protection Agency's peer and administrative review policies and approved for presentation and publication. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

FOREWORD

The Environmental Protection Agency was created because of increasing public and governmental concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimony to the deterioration of our natural environment. The complexity of the environment and the interplay between its components require a concentrated and integrated attack on the problem.

Research and development is the first necessary step in problem solution; it involves defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems to prevent, treat, and manage wastewater and the solid and hazardous waste pollutant discharges from municipal and community sources; to preserve and treat public drinking water supplies, and to minimize the adverse economic, social, health and aesthetic effects of pollution. This publication is one of the products of that research--a vital communications link between the researcher and the user community.

These Proceedings present the results of completed and ongoing research projects concerning the land disposal of hazardous waste.

Francis T. Mayo
Director
Municipal Environmental
Research Laboratory

PREFACE

These Proceedings are intended to disseminate up-to-date information on extramural research projects concerning land disposal, incineration, and treatment of hazardous waste. These projects are funded by the U.S. Environmental Protection Agency's Office of Research and Development and have been reviewed in accordance with the requirements of EPA's Peer and Administrative Review Control System.

ABSTRACT

The Ninth Annual Research Symposium on land disposal, incineration, and treatment of hazardous wastes was held in Ft. Mitchell, Kentucky, May 2, 3 and 4, 1983. The purposes of the symposium were (1) to provide a forum for a state-of-the-art review and discussion of ongoing and recently completed research projects dealing with land disposal, incineration, and treatment of hazardous wastes; (2) to bring together people concerned with hazardous waste management who can benefit from an exchange of ideas and information; and (3) to provide an arena for the peer review of the Solid and Hazardous Waste Research Division's and the Industrial Pollution Control Division's research programs in hazardous waste management. These Proceedings are a compilation of papers presented by the symposium speakers.

The symposium proceedings are being published as two separate documents. In this document, Land Disposal of Hazardous Waste, seven technical areas are covered. They are as follows:

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(6) Cost/Economics
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TECHNICAL RESOURCE DOCUMENTS FOR HAZARDOUS WASTES

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ABSTRACT

The Environmental Protection Agency is preparing documents for permit officials responsible for hazardous waste landfills, surface impoundments, land treatment facilities and piles. The Technical Resource Documents (TRDs) describe current technologies and methods for evaluating the performance of the applicant's design in the areas of liners, leachate management, closure, covers, and water balance. These documents are basically a compilation of all research efforts of the Solid and Hazardous Waste Research Division (SHWRD) to date and are being published or developed to assist in the implementation of the regulations concerning hazardous waste disposal facilities. The RCRA Guidance Documents being prepared by the Office of Solid Wastes (OSW) will present design and operating specifications which the Agency believes comply with Design and Operating Requirements and the Closure and Post-Closure Requirements contained in Part 264 of the regulations. The information and guidance presented in these documents constitute a suggested approach for review and evaluation based on good engineering practices. There may be alternative and equivalent methods for conducting the review and evaluation. However, if the results of these methods differ from those of the Environmental Protection Agency's method, they may have to be validated by the applicant.

INTRODUCTION

Land disposal of hazardous waste is subject to the requirements of subtitle C of the Resource Conservation and Recovery Act of 1976. This Act requires that the treatment, storage, or disposal of hazardous waste be carried out in accordance with a permit. Owners or operators of new facilities must apply for and receive a permit before beginning operation of such a facility.

In reviewing and evaluating the permit application, the permit official must make all decisions in a well defined and well documented manner. Once an initial decision is made to issue or deny a permit, the subtitle C regulations require preparation of either a statement of basis or a fact sheet that discusses the reasons behind the decision, and becomes part of the permit review process specified in 40 CFR 124.6-124.20.

Eight TRDs have been completed to date. Six of the TRDs are related to landfills, and one document each is related to surface impoundments and land treatment. A listing of these documents is shown below, along with a brief description, publication number, and the project officer's name in parentheses.

TRD 1: EVALUATING COVER SYSTEMS FOR SOLID AND HAZARDOUS WASTE (SW-867) - This document presents a procedure for evaluating cover systems for solid and hazardous waste. It contains a checklist, with supporting documentation, that a permit writer can use to evaluate proposed cover systems. *055-000-00228-2 (R. E. Landreth)

TRD 2: HYDROLOGIC SIMULATION ON SOLID WASTE DISPOSAL SITES (SW-868) - This document provides a computer package to aid planners and designers by simulating hydrologic characteristics of landfill

covers to predict percolation as a function of cover design and climate.
*055-000-00225-8 (D. C. Ammon)

TRD 3: LANDFILL AND SURFACE IMPOUNDMENT PERFORMANCE EVALUATION (SW-869) - This document describes how to evaluate leachate collection systems using compacted clay or synthetic liners to determine how much leachate will be collected and how much will seep through the liner into underlying soils. The adequacy of sand and gravel drain layers, slope, and pipe spacing are also covered.
*055-000-00233-9 (M. H. Roulier)

TRD 4: LINING OF WASTE IMPOUNDMENT AND DISPOSAL FACILITIES (SW-870) - This document provides information and guidance on liner systems. It discusses waste, liner types, compatibility, liner selection, specifications, design of leachate collection systems, and case study analysis methodology. It also includes a glossary of liner system related terms.
*055-000-00231-2 (R. E. Landreth)

TRD 5: MANAGEMENT OF HAZARDOUS WASTE LEACHATE (SW-871) - This document discusses leachate composition, leachate generation, selected management options, available treatment technologies, unit-treatment options, and system economics. It presents management options that a permit writer or hazardous waste landfill operator may consider in controlling and treating leachate.
*055-000-00224-0 (S.C. James)

TRD 6: GUIDE TO THE DISPOSAL OF CHEMICALLY STABILIZED & SOLIDIFIED WASTES (SW-872) - This document provides basic information on stabilization/solidification of industrial wastes to insure safe burial of wastes containing harmful materials. A summary of major physical and chemical properties of treated wastes is presented along with a listing of major suppliers of stabilization/solidification technology including a summary of each process.
*055-000-00226-6 (R. E. Landreth)

TRD 7: CLOSURE OF HAZARDOUS WASTE SURFACE IMPOUNDMENTS (SW-873) - This document discusses and references the methods, tests, and procedures involved in closing a surface impoundment. Problems of abandoned impoundments causing environmental degradation and discussed. Closure methods such as waste removal and consolidating the waste on site and securing the site as a landfill are also discussed.
*055-000-00227-4 (M. H. Roulier)

TRD 8: HAZARDOUS WASTE LAND TREATMENT (SW-874) - This document discusses land treatment medium, characteristics of hazardous waste, allowable waste loadings, facility planning for land treatment, land treatment permit processes, closure, and items to be considered during permit evaluation.
*055-000-00232-1 (C.C. Wiles)

Each of the completed TRDs is described in greater detail in the following section of this paper.

TECHNICAL RESOURCE DOCUMENTS CURRENTLY AVAILABLE

Evaluating Cover Systems for Solid and Hazardous Waste (SW-867)

A critical part of the sequence of designing, constructing, and maintaining an effective cover over solid and hazardous waste is the evaluation of engineering plans. This TRD presents a procedure for evaluating closure covers on solid and hazardous wastes. All aspects of covers are addressed in detail to allow for a complete evaluation of the entire cover system.

Covers may be evaluated for conformance to requirements for closure covers by the following eleven (11) general procedures in sequence:

1) examine soil test data,
2) examine topography,
3) examine climate data,

---

*Drafts of the above documents have been released for public comment and all have been revised so as to incorporate the public's comments and reviews. They are currently being published and the reports will be available from GPO by requesting the stock number. Copies can be obtained for a price from the:

Superintendent of Documents
U.S. Government Printing Office
Washington, DC 20402
(202) 783-3238

4) evaluate composition,
5) evaluate thickness,
6) evaluate placement,
7) evaluate configuration
8) evaluate drainage,
9) evaluate vegetation,
10) evaluate post-closure plan, and
11) evaluate contingencies plan.

This document describes current technology for landfill covers. For a landfill, these state that: 1) runoff that has touched hazardous waste must be collected and treated, 2) waste received must be analyzed, 3) each waste cell's contents, depth, location, and dimensions must be documented, and 4) a closure and post-closure plan is required to address control of pollutant migration, surface water infiltration, and erosion.

Guidance is provided on: characteristics and type of waste, location of fill with respect to potential environmental impact of pollutant migration, climate and precipitation, cover material and thickness, cover slope and vegetation, maintaining the final cover, maintaining groundwater, monitoring the gas collection system, and restricting access to the landfill. There are 36 specific steps, regarding the preceding factors, which should be followed in evaluating a permit for a cover for hazardous waste.

Hydrologic Simulation on Solid Waste Disposal Sites (SW-868)

Percolation and runoff of precipitation at solid waste disposal sites create a potential for ground and surface water contamination with leachate. The proper landfill site design and operational approach is to minimize or eliminate percolation through the solid waste and thus control the formation of leachate.

The purpose of this TRD is to provide an interactive computer program for simulating the hydrologic characteristics of a solid and hazardous waste disposal site operation. A large number of cities within the U.S. for which five years of climatic records exist have been put on tape for easy access and can be used in lieu of on-site measurements. In addition, the model stores many default values of parameter estimates which can be used when measured and existing data files are not available. The user must supply the geographic location, site area and hydrologic length, the characteristics of the final soil and vegetative cover, and default overrides where deemed necessary. From minimal input data, the model can simulate daily, monthly, and annual runoff, deep percolation, temperature, soil water, and evapotranspiration.

The model, which is a modification of the Soil Conservation Service (SCS) number method for predicting runoff and the hydrologic portion of the U.S. Department of Agriculture, Science and Education Administration (USDA-SEA) hydrologic model entitled "Chemicals, Runoff, and Erosion From Agricultural Management Systems (CREAMS)," has been modified to conform to the design characteristics of solid and hazardous waste disposal sites. The model takes engineering, hydrologic, and climatologic input data in the form of rainfall, average temperature, solar radiation, and leaf area indices and characteristics of cover material and performs a sequential analysis to derive a water budget including runoff, percolation, and evapotranspiration.

The user can specify up to three soil layers and may also specify a membrane liner at the base of the cover. The decreasing effectiveness of the liner is simulated. The model is designed for use in a conversational manner, that is, the user interacts directly with the program and receives output immediately. No prior experience with computer programming is required. All commands necessary to use the model are presented in the user's manual. The model can also be run in batch mode, which requires some computer programming experience.

Landfill and Surface Impoundment Performance Evaluation (SW-869)

This TRD describes how to evaluate the capability of various liner and drain designs to control leachate release. The author has allowed for the widely varied technical backgrounds of his intended audience by presenting, in full, the rigorous mathematics involved in reaching his final equations. Thus, any evaluator can take full advantage of the manual up to the level of his own mathematical proficiency.

This evaluation system considers the transport of liquids through simple modular configurations. The important parts of these modules are identified as the Liquid Transport Control (LTC) system, and the Diversion Interface (DI). The mathematics consider the efficiency with which the LTC and DI components convert leachate flow from vertical to horizontal. The extent of ponding on a bottom liner is considered in relation to the position and effectiveness of the drainage system.

The procedures described in the document should allow an evaluator to determine the adequacy of design for:

1) compacted clay liners or synthetic liners intended to impede the vertical flow of fluids,

2) sand or gravel drainage layers intended to convey liquids laterally into collection systems,

3) slopes on such liner systems, and

4) spacings of collector drains.

The evaluation procedure is independent of the structure of the regulation it supports. If regulations specify acceptable rates of release for leachate, or efficiencies of leachate collection systems, calculation results may be used directly to determine if the landfill is acceptable. However, if the regulations describe acceptable environmental impact, results from the evaluation procedure can be used as input for further evaluation in other manuals to determine if the impact of the landfill is acceptable.

Lining of Waste Impoundment and Disposal Facilities (SW-870)

This document provides information on performance, selection, and installation of specific liners and cover materials for specific disposal situations, based upon the current state-of-the-art of liner technology and other pertinent technologies. It contains descriptions of wastes and their effects on linings, a full description of various natural and artificial liners; service life and failure mechanisms; installation problems and requirements of liner types; costs of liners and installation; and tests that are necessary for pre-installation and monitoring surveys.

Described in the report are potentially useful lining materials and their associated technologies, including re-molded and compacted soils and clays, admixes, polymeric membrane liners, sprayed-on liners, soil sealants, and chemisorptive liners. The specific characteristics of these liners in service environments with various types of wastes are discussed, particularly with respect to compatibility with wastes, permeability to water and waste, failure mechanisms, and service life.

Design and construction of waste facilities with various types of linings are described, emphasizing installation of membrane liners and their problems. Special problems associated with the design and construction of solid waste disposal sites are considered. The subjects of leachate collection above the liner, gas control, and top-seals are addressed.

Several processes for selecting a specific liner or various satisfactory liners for a given disposal site are proposed. These include the use of compatibility tests, moderate duration exposure tests, soil conditions tests, costs, etc. Methods for the preparation of specifications covering the selected liners or groups of liners are suggested.

In the appendices, data are presented on liners and wastes, compatibility studies, manufacturers and suppliers, specifications, test methods, along with indices to lined disposal sites. As new technology is developed, and as experience in the use of liners becomes available, the manual will be upgraded on a chapter-by-chapter basis.

Management of Hazardous Waste Leachate (SW-871)

This document has been prepared to provide guidance for permit officials and disposal site operators on available management options for controlling, treating, and disposing of hazardous waste leachates. It discusses considerations necessary to develop sound management plans for leachate generated at surface impoundments and landfills. Management may take the form of leachate collection and treatment, or pre-treatment of the waste.

The manual addresses areas that must be considered in evaluating a leachate management option: leachate generation and composition, and available technologies for treatment of leachate and hazardous waste.

Leachate composition is examined for several hazardous waste landfills, synthetic leachates from lab studies, and sanitary landfill leachates. The expected composition of the leachate and the concentrations of the pollutants in the leachate are presented along with possible guidelines for permit writers to use in determining the relative hazards of a particular leachate.

A key section enumerates factors which influence treatment process selections and provides a suggested approach for systematically addressing each. Selected hypothetical and actual leachate situations are used as examples for applying the approach to the selection of appropriate treatment processes.

Other sections address monitoring, safety, contingency plans/emergency provisions, equipment redundancy/backup, permits, and surface runoff.

Guide to the Disposal of Chemically Stabilized and Solidified Waste (SW-872)

Stabilization/solidification of industrial waste is a pre-treatment process designed to insure safe disposal of wastes containing harmful materials. The purpose of this TRD is to provide guidance in the use of chemical stabilization/solidification techniques for limiting hazards posed by toxic wastes in the environment, and to assist in the evaluation of permit applications related to this disposal technology. The document addresses the treatment of hazardous waste for disposal or long term storage and surveys the current state and effectiveness of waste treatment technology. A summary of the major physical and chemical properties of treated wastes is presented. A listing of major suppliers of stabilization/solidification technology and a summary of each process is included.

This guide provides the background information needed for waste generators and regulatory officials to determine the testing program and/or product information necessary for them to make the best engineering judgements concerning the long term effectiveness in site specific conditions. Some familiarity with general soil characteristics, water balance, climatic conditions, and fundamentals of leachate generation would be helpful to the user.

Closure of Hazardous Waste Surface Impoundments (SW-873)

"Closure of Hazardous Waste Surface Impoundments" presents a listing of closure plan and post-closure care considerations and details for surface impoundments containing hazardous wastes. It is written primarily for staff members in EPA Regional Offices or state regulatory offices, who are charged with evaluating and approving closure plans for surface impoundments under regulations of the Resource Conservation and Recovery Act of 1976. Methods of assessing site closure considerations are documented.

The guide describes and references the methods, tests, and procedures involved in closing a site in such a manner that (a) minimizes the need for further maintenance, and (b) controls, minimizes, or eliminates, to the extent necessary to protect human health and the environment, post-closure escape of hazardous waste, waste constituents, leachate, contaminated rainfall or waste decomposition products to groundwater, surface water, or the atmosphere. Problems that have been overlooked in abandoned impoundments and have caused environmental damage are discussed. The techniques involved are pertinent to closing an impoundment either by removing the hazardous waste or by consolidating the waste on-site and securing the site as a landfill. Technical criteria for implementing the closure, specifically those regarding aspects substantially different from a landfill, are given. Relevant literature or procedures are documented for more in depth review.

Hazardous Waste Land Treatment (SW-874)

Land treatment, which involves using the surface soil as the treatment medium, is already widely practiced by some industries for handling their hazardous wastes. However, the lack of systematic study or monitoring of many past or present facilities has limited the knowledge and data base with regard to the important parameters and interactions. Additionally, many potentially land treatable wastes have not been tested or have been examined only under a limited range of conditions. Therefore, information is needed on site selection, waste characteristics, optimum soil and climatic conditions for degradation of organic constituents, application rates and scheduling decomposition products, and the contingency for environment contamination. Potential problems include worker health and safety, organic components, water pollution hazards, and local atmospheric emissions.

Land treatment of hazardous waste has not been under close scrutiny for a long enough period of time to acquire numerous documented failures resulting in environmental pollution. The potential for such failures due to the lack of proper design and/or management is evident from research conducted on the land treatment of other non-hazardous waste materials. For land treatment to be an effective system, the process must operate within a narrow range of parameters. Exceeding them could result in the uncontrolled release of pollutants to the environment. The objectives of "Hazardous Waste Land Treatment" are to describe current technology and to provide methods for evaluating the performance of an applicant's hazardous waste land treatment facility design. Land treatment is approached comprehensively from initial site selection through final closure, and additional informational sources are referenced liberally.

FUTURE TECHNICAL RESOURCE DOCUMENTS

Additional TRDs now being developed or in planning stages by Office of Research and development:

A listing of these documents is shown below, along with a brief description and the project officers name in parentheses.

1. SOIL PROPERTIES, CLASSIFICATION AND HYDRAULIC CONDUCTIVITY TESTING

This report is a compilation of available laboratory and field testing methods for the measurement of hydraulic conductivity (permeability) of soils. Background information on soil classification, soil water, and soil compaction are included along with descriptions of sixteen methods for determination of saturated or unsaturated hydraulic conductivity.
(M. H. Roulier)

2. SOLID WASTE LEACHING PROCEDURE MANUAL

This project is developing laboratory batch procedures for extracting or leaching a sample of solid waste so that the composition of the lab leachate is similar to the composition of leachate from waste under field conditions.
(M. H. Roulier)

3. BATCH SOIL PROCEDURE TO DESIGN CLAY LINERS FOR POLLUTANT REMOVAL

This project is studying the feasibility of using soil/leachate batch adsorption procedures for designing compacted clay liners to remove/retain known amounts of pollutants, and will contribute to guidance for designing and evaluating clay liners to limit pollutant release from landfills.
(M. H. Roulier)

4. METHODS FOR THE PREDICTION OF LEACHATE PLUME MIGRATION AND MIXING

This project is developing a variety of computer programs, nearly all of which are designed for hand-held calculators and microcomputers. The programs permit prediction of leachate plume migration and groundwater recharge. The document also contains discussions of sorption, case historical and a field study.
(M. H. Roulier)

5. HYDROLOGIC EVALUATION OF LANDFILL PERFORMANCE (HELP) MODEL

The original waste disposal site hydrologic model entitled, "Hydrologic Simulation on Solid Waste Disposal Sites" is being modified. This update will incorporate the two-dimensional aspects of landfill cover systems, as well as the addition of the leachate collection system. This second generation model will be entitled, "Hydrologic Evaluation of Landfill Performance (HELP) Model."
(D. C. Ammon)

CONCLUSION

The TRDs that are being prepared by SHWRD are a series of documents which represent the Best Engineering Judgement

(BEJ) for the design, operation, and closure of hazardous waste facilities. Eight documents have been completed with five more either in process or planned by the Office of Research and Development. These documents have been directed primarily for use by permit writers for evaluating facility designs and potential performance of new waste disposal facilities. The TRDs present the sum total of the body of information and experience gained by the Agency over the years on a given topic. As such, they contain factual summaries concerning the experience and effectiveness of design alternatives, covering what has been found not to work as well as what has been found to be effective. The TRDs can be considered as technical background or development documents supporting the RCRA guidance documents and regulations.

The project officers can be contacted by writing or telephoning the: U. S. EPA, Municipal Environmental Research Laboratory, Solid and Hazardous Waste Research Division, 26 West St. Clair Street, Cincinnati, Ohio 45268, Telephone (513) 684-7871.

CURRENT RESEARCH ON LAND DISPOSAL OF HAZARDOUS WASTES

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ABSTRACT

The Solid and Hazardous Waste Research Division (SHWRD), Municipal Environmental Research Laboratory, U.S. Environmental Protection Agency, in Cincinnati, Ohio, has responsibility for research in solid and hazardous waste management with respect to land disposal of wastes. To fulfill this responsibility, the SHWRD is developing concepts and technology for new and improved systems of solid and hazardous waste land disposal; is documenting the environmental effects of various waste disposal practices; and is collecting data necessary to support implementation of disposal guidelines mandated by the "Resource Conservation and Recovery Act of 1976 (RCRA)" PL 94-580. Also, SHWRD is collecting data on existing construction technologies and applying these techniques to the containment of pollutants emanating from uncontrolled dump sites. This is being done to assist in the implementation of the "Comprehensive Environmental Response, Compensation and Liability Act of 1980" (CERCLA) PL 96-510. This paper will present an overview of the land disposal aspects of the SHWRD Hazardous Waste Program Plan and will report the current status of work in the following categorical areas:

A. LANDFILLS
    1. Pollutant Generation
    2. Pollutant Movement
    3. Pollutant Control
    4. Pollutant Treatment
B. LANDFILL ALTERNATIVES
    1. Surface Impoundments
    2. Underground Mine Disposal
C. UNCONTROLLED SITES/REMEDIAL ACTION
D. COST/ECONOMIC ASSESSMENT

INTRODUCTION

The waste residual disposal research strategy, encompassing state-of-the-art documents, laboratory analysis, bench and pilot studies, and full-scale field verification studies is at various stages of implementation. Over the next 2 years the research will be reported as guidance documents for user communities. The waste disposal research program is currently developing and compiling a data base for use in the development of guidelines and standards for waste residual disposal to the land as mandated by the "Resource Conservation and Recovery Act of 1976" (RCRA). Permit Writer's Guidance Manuals, which will present design and operating specifications which the Agency believes comply with design and operating requirements and the closure and post closure requirements contained in Part 264 of the regulations are currently being prepared by the Office of Solid Waste in Washington, D.C. Technical Resource Documents (TRD) in support of the Guidance Manuals are also being prepared by the Office of Research and Development in specific areas to provide current technologies and methods for evaluating the performance of the applicants' design. A separate paper entitled, "Technical Resource Documents for Hazardous Wastes" has been accepted for presentation at the Ninth Annual Research Symposium on Land Disposal, Incineration and Treatment of Hazardous Wastes. Therefore, no discussion of the TRDs will be presented in this paper.

Current hazardous waste land disposal research has been divided into four general areas: (a) Design Considerations for Current Landfill Disposal Techniques; (b) Alternatives to Current Landfill Disposal Techniques; (c) Remedial Action for Minimizing Pollutants from Uncontrolled Sites; (d) Economic Assessment of Hazardous Waste Disposal Practices and Alternatives.

The waste residual research program has been discussed in the previous eight symposia. These symposia describe the land disposal of both municipal and hazardous waste. The report of the previous most recent symposium is entitled "Research on Land Disposal of Hazardous Waste: Proceedings of the Eighth Annual Research Symposium," March 8-10, 1982, Fort Mitchell, Kentucky, EPA-600/9-82-002.

LANDFILLS

Pollutant Generation

The overall objective of this research activity is to address techniques for leaching a waste sample to obtain leachate similar to that which will occur when the waste is landfilled. A leaching procedure is being developed for use in determining which pollutants will be of concern in movement of leachates out of the landfill and for evaluating leachate treatment schemes in order to better develop pollutant control technology. A Technical Resource Document (TRD) entitled "Landfill and Surface Impoundment Performance Evaluation" (SW-869) reflects current state-of-the-art in this area and is available from the Government Printing Office (055-000-00233-9).

One completed effort (1)* in the waste leaching area was directed toward applicable analytical methods for leachate analysis. Physical and chemical methods were evaluated for their suitability in analyzing of contaminated industrial leachate streams. The results of this completed effort were published in a report entitled "Analytical Methods Evaluation for Applicability in Leachate Analysis," EPA-600/2-81-046, March 1981.

A second ongoing effort (2) is developing a detail laboratory procedure for extracting or leaching a sample of solid waste so that the composition of laboratory leachate is similar to the composition of leachate from the waste under field conditions. It is anticipated that this effort will be identified as a Technical Resource Document (TRD) entitled "Solid Waste Leaching Procedure Manual" with anticipated publication late in FY 1983. A subsequent study will be implemented (2) in FY 1983 to compare batch and column procedures for waste leaching.

A third ongoing effort (7) was the development of a two-dimensional surface drainage system evaluation model for hazardous waste disposal facilities. A Technical Resource Document entitled "Hydrologic Simulation on Solid Waste Disposal Sites" (SW-868) reflects the current state-of-the-art knowledge in this area and is available from the Government Printing Office (055-000-00225-8). In addition to the development of this model, a detailed evaluation of various designs was conducted to assist in the design of numerical performance information for cover systems after closure and for leachate collection systems. The completed first phase of this project includes four tasks: 1) evaluation of subsurface drainage system designs for establishment of numerical performance standards; 2) development of user oriented two-dimensional subsurface drainage system evaluation capabilities; 3) user support for the current version of the Hydrologic Simulation on Solid Waste Disposal Sites; and 4) documentation, report preparation, and technical coordination. A draft TRD report entitled "Hydrologic Evaluation of Landfill Performance (HELP) Model" has been prepared with anticipated publication in late FY 1983. The second phase effort for additional technical support and model verification is now underway.

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* Parenthesis numbers refer to the project officers who is monitoring this effort and whose name is listed immediately following this paper. The project officer can be contacted for additional information.

A fourth completed effort (4) is a study of the effectiveness of cover materials to prevent/control infiltration of water into waste disposal sites. Covers made of synthetic materials, natural materials, and combinations of both are being studied for their effectiveness. Disturbances to covers such as vegetation growth, burrowing animals, and varying climatic conditions are being considered. The final report entitled "Design and Construction of Covers for Solid Waste Landfills" is available (EPA 600/2-79-165) August 1979. A TRD entitled "Evaluating Cover Systems for Solid and Hazardous Waste" (SW-867) reflects the current state-of-the-art in this area and is available from the Government Printing Office (055-000-00228-2).

Co-Disposal: The overall objective of the co-disposal activity is to assess the impact of the disposal of industrial waste materials with municipal solid waste. Since the environmental effects from landfilling result from not only the soluble and slowly soluble materials placed in the landfill but also the products of chemical and microbiological transformation, these transformations should be a consideration in management of a landfill to the extent that they can be predicted or influenced by co-disposal operations.

One ongoing effort (3) involves a study of the factors influencing (a) the rate of decomposition of solid waste in a sanitary landfill, (b) the quantity and quality of gas and leachate produced during decomposition, and (c) the effect of admixing industrial sludges and sewage sludge with municipal refuse. Some of the factors under investigation are: varying moisture infiltration rates, adding pH buffering compounds, prewetting the wastes and varying ambient temperatures. A combination of municipal solid waste and various solid and semi-solid industrial wastes were added to several field lysimeters. The industrial wastes being investigated are: petroleum sludge, battery production waste, electroplating waste, inorganic pigment sludge, chlorine production brine sludge, and a solvent-based paint sludge. Also, municipal digested primary sludge dewatered to approximately 20 percent solids was utilized at three different ratios. The results of approximately nine years of data generated under this effort have been reported in several proceedings of the annual research symposia from the Solid and Hazardous Waste Research Division. An annual report entitled "Evaluation of Landfilled Municipal and Industrial Hazardous Waste" has been received and is currently being reviewed.

A second completed effort (4) related to the co-disposal of chemically treated and untreated industrial wastes in a municipal refuse environment. Large lysimeters were being utilized to determine the difference in leachate quality. Results have indicated that co-disposal of treated or untreated electroplating sludge with MSW does not affect leachate quality. Co-disposal of calcium fluoride/sewage sludge with MSW apparently improves leachate quality. The final report is scheduled for publication in September 1983.

Pollutant Movement

The objective of pollutant movement work is to develop predictive relationships which can be used in the design and regulation of disposal facilities for municipal and hazardous solid waste to insure that any releases to the environment will not be detrimental.

Current research is intended to develop tools for designing soil liners that limit pollutant release to a predictable minimum. The application is primarily for landfills, but the information is also useful in design of soil liners for surface impoundments and in predicting the amounts of pollutants that will pass below the zone of incorporation at land disposal sites. The work is proceeding in two parallel phases. In the first, methods for predicting movement of liquid (leachate) are being developed and improved and in the second, methods are being developed for predicting how well soil liners will remove pollutants from any leachate that seeps through the liner. Work is in progress on empirical predictive techniques using samples of wastes and soils from locations of specific interest. This approach appears to be the most promising in order to integrate the effect of waste and soil characteristics on pollutant retention processes. The precision and accuracy that will be achieved by this method remains to be determined.

One completed effort (2) examined the extent to which hazardous substances from specific industrial and flue gas cleaning (FGC) wastes would migrate into groundwater at disposal sites. Procedures for conducting such examinations have been developed. A sequential batch leaching/soil adsorption procedure was developed which provides information comparable to that obtained from soil column studies, but in a much shorter time. The results of this effort have been reported in several preveious symposia proceedings; a complete report of the project will be published in a report entitled "Migration of Hazardous Substances in Soil" in FY 1983.

A second completed effort (2) was the development and testing of numerical simulation models for predicting movement of solutes in saturated and unsaturated soils. The accuracy and computational efficiency of several existing and newly developed numerical schemes for solving flow and transport equations were compared. Additionally, a closed-form analytical model was developed for predicting the unsaturated hydraulic conductivity from available soil moisture retention data. Considerations in selection of numerical models, including the effects of soil types, flow regime and magnitude of soil solute interaction parameters are discussed in a final report entitled "Mass Transport in Saturated-Unsaturated Media," which is being prepared for publication in September 1983.

A third completed effort (2) was the development of user oriented models for predicting movement in soil as a basis for improving selection of sites for disposing of solid and hazardous wastes. Long term movement rates were correlated with soil and leachate properties to develop regression equations forming a basis for a simplified predictive tool. The work has been completed and a report entitled "Behavior of Cd, Ni, and Zn in Single and Mixed Combinations in Landfill Leachates" describing use of this tool in conjunction with soil column tests to predict solute movement in soil is being prepared for publication in FY 1983.

A fourth completed effort (2) studied vertical and horizontal contaminant migration of Zn, Cd, Cu and Pb at three secondary zinc smelting plants and one organic chemical manufacturing plant. Migration patterns were defined using soil coring and monitoring well techniques. Soil coring was determined to be an investigative tool, but not suitable by itself for routine monitoring of waste disposal activities. The results of this study are currently being prepared for publication in a report entitled "Field Verification of Toxic Wastes Retention by Soils at Disposal Sites."

A fifth completed effort (2) was the determination of the attenuation mechanisms and capacity of selected clay minerals and soils for hexachlorocyclopropentadiene (HCCPD) and "hex" wastes. Also, effects of caustic-soda brine on the attenuation of solubility of HCCPD were researched. The development of a chemical model to predict HCCPD migration through soil was pursued. Mobility of HCCPD in soils was independently assessed by use of soil thin-layer chromatography and column leaching techniques. This study has been completed and the draft final report entitled "Assessment of Soil, Clay, and Caustic-Soda Effects on Land Disposal of Chlorinated-Hydrocarbon Wastes" is currently undergoing peer review for publication in FY 1983.

A sixth completed effort (2) studied organic contaminant attenuation by selected clay minerals and coal chars. Initial work was with Polychlorinated biphenyls (PCBs); subsequent efforts were with Hexachorobenzene (HCB) and Polybrominated biphenyls (PBB). The results of the first phase of this effort were published in a report entitled "Attenuation of Water-Soluble Polychlorinated Biphenyls by Earth Materials," EPA-600/2-80-027, March 1980. The results of the second phase were published under the title "Attenuation of Polybrominated Biphenyls and Hexachlorobenzene by Earth Materials," EPA-600/2-81-191, March 1981.

A seventh completed effort (2) is looking at the categories of water movement that occur in connection with various types of landbased disposal systems. Methods of soil hydraulic conductivity determination and interpretation are discussed. The results of the effort are currently being prepared in the form of a technical resource document (TRD) entitled "Soil Properties, Classification, and Hydraulic Conductivity Testing." This TRD will be released by the Office of Solid Waste in FY 83 for public comment.

An eighth ongoing effort (4) has evaluated the effects of organic leachates on clay liner permeability and procedures for rapidly testing these effects have been outlined. The initial results of this effort have been published in a report entitled "Effects of Organic Solvents on the Permeability of Clay Soils," EPA 600/2-83-016, April 1983..

A ninth ongoing effort (2) is currently underway to determine how accurately the EPA Gas Movement Model predicts the maximum distance that methane gas will move through soils adjacent to landfills and how accurately this model will predict the relative effectiveness of control systems (e.g., trenches, wells, barriers) for minimizing methane gas movement. Methane movement was measured at three selected landfills. With data from each landfill, the model will be used to predict the maximum extent of methane movement. The measured and predicted methane movements will be compared, reasons for any differences analyzed, and the accuracy and effort of use for the model determined. At one of the landfills, active and passive control systems are being installed. The observed degree of control and that predicted by the model are being compared. The project is scheduled for completion in March 1983. The report will be entitled "Field Verification of Gas Migration Predictive Methods and Design Criteria for Gas Controls."

A tenth completed effort (2) has resulted in establishment of guidelines for design of gas migration control devices for sanitary landfills. The migration control devices studied included trenches venting under natural convection, trenches with exhaust pumping, trenches with recharge pumping, barriers, hybrid systems consisting of a barrier with a pumped (exhaust or recharge) or unpumped trench on the landfill site, and pumped (exhaust or recharge) pipe vents. Computer codes developed under a previous study (i.e., Moore and Alzaydi, 1977; and Moore and Rai, 1977) were modified to incorporate pressure flow as well as diffusional flow. The results of this completed effort currently in draft stage will be published in a report entitled "Gas Control Design Criteria" in FY 1983.

An eleventh ongoing effort (2) is concerned with developing a contaminant/soil interaction protocol. Work on this project will include the collection, evaluation, and testing of procedures for conducting batch adsorption studies with leachates and soils to determine the amounts of pollutants that will be retained by clay liners in disposal facilities. The results of this project will be put into a TRD entitled "Batch Soil Procedure to Design Clay Liners for Pollutant Removal" for use in designing and evaluating clay liners to limit pollutant release from landfills.

A twelfth ongoing effort (2) is concerned with developing a TRD entitled "Containment/Soil Interaction Protocol." The project will address: 1) to what degree leachate concentrations will be reduced by mixing with ground water in the vicinity of waste disposal sites; 2) the direction of movement and shape of leachate plumes; and 3) the types of models that are appropriate for predicting movement of solutes in ground water. An interim report entitled "Methods for Prediction of Leachate Plume Migration and Mixing" is now being prepared for release by the Office of Solid Waste for public comment.

A thirteenth ongoing effort (8) is concerned with the development of a handbook designating state-of-the-art procedures and techniques of control of leachate plume migration including methods for priority use rankings based on site conditions, risk assessments, cost and long term applications. Leachate migration controls that are being studied include impermeable barriers, slurry walls, grout curtains, groundwater pumping, water table adjustment, plume containment, subsurface drains, bioreclamation, drainage ditches, liners and leachate treatment.

Pollutant Control

The overall objective of this research activity is to reduce the impact of pollution from wastewater disposal sites by technology that minimizes, contains, or eliminates pollutant release and leaching from waste residuals disposed to the land. The pollutant control studies are determining the ability of in-situ soils and natural soil processes to attenuate leachate contaminants as the leachate migrates through the soil from landfill sites. The studies are also determining how various synthetic and admixed materials may be utilized as liners to contain and prevent leachates from migrating from landfill sites.

Natural Soil Processes: The attenuation by natural soil processes of pollutants from hazardous waste and municipal refuse disposal sites is being performed in the controlled lab studies previously discussed in the section on pollutant movement.

Liners/Membrane/Admixtures: The liner/membrane/admixture technology (4) has been studied to evaluate suitability for eliminating or reducing leachate from landfill sites of municipal or industrial hazardous wastes. The test program evaluated the chemical resistance and durability of the liner materials over 12 and 36-month exposure periods to leachates derived from industrial waste, sulfur oxides (SO_x) wastes, and municipal solid wastes. Acidic, basic, and neutral solutions were utilized to generate industrial waste leachates.

The results of these tests along with a discussion of the overall hazardous waste liner material program are presented in a report entitled "Liner Materials Exposed to Hazardous and Toxic Sludges First Interim Report," EPA-600/2-77-091, June 1977.

A second effort (4) relates to the types of materials tested for use as liners for sites receiving sludges generated by the removal of SO_x from flue gases of coal burning power plants. The admixed materials consisted of the following: lime; cement with lime; polymeric bentonite blend (M179); gray powder-quartec (UF); asphaltic concrete; TACSS 020; TACSS 025; TACSS C400; and TACSS ST. The prefabricated membranes liner materials consisted of the following: elasticized polyolefin; black neoprene - coated nylon; and black neoprene - reinforced fabric. The spray-on liner materials consisted of the following: polyvinyl acetate; natural rubber latex; natural latex; polyvinyl acetate; asphalt cement; and molten sulphur. A final report has been published entitled "Effect of Flue Gas Cleaning Sludges on Selected Liner Materials," EPA-600/2-81-098, July 1981

A third effort (4) is an ongoing study to assess actual field procedures utilized in (a) preparing the support sub-base soil structure for liners and (b) placing the various liner materials common to projects requiring positive control of fluid loss. Information obtained to date includes: methods and equipment used to prepare the subgrade and to place the liner material; specific design and construction considerations; and special problems encountered during installation. The final report entitled "Case Studies for Lined Impoundments" is being prepared for publication in FY 1983.

A fourth completed effort (4) was concerned with determining the soil requirements to act as bedding and protective covers for flexible membranes. Experiments were conducted using a variety of flexible membranes, thicknesses and densities of base and sub-base sands and soils, and then trafficked employing three different vehicles representative of those used for landfill construction. A design manual, applicable to the majority of the country, will be developed which will provide a design engineer with the data necessary to determine the most economic soil requirements above and below a flexible membrane. The final project report entitled "Laboratory Model Studies Conducted to Determine Soil Bedding Requirements for Flexible Membranes" is being prepared for publication in FY 1983.

A fifth ongoing effort (4) responds to the need for support of the guidelines and hazardous waste criteria mandated under RCRA. This project has been designed to provide the EPA with data to enable annual revisions to the landfill liner TRDs now being finalized. Furthermore, it will provide assistance in permit application evaluation, assessment of performance and expert testimony.

A sixth effort (4), now completed, was primarily concerned with the evaluation of specific technologies (chemical liners) for the disposal and recovery of sludges from the metal finishing industry. Specifically, this effort evaluated the use of three chemical liners, i.e., agricultural limestone, fly ash, and hydrous oxides of iron in minimizing the pollution potential from an electroplating sludge. Data have been developed for mass flux values. The final report will be available in September 1983.

A seventh effort (2), now completed, relates to a laboratory study of agricultural limestone and hydrous oxides of Fe to evaluate their use as landfill liner materials to minimize the migration of metal contaminants. The results of this effort have been published in a report entitled "Liners of Natural Porous Materials to Minimize Pollutant Migration," EPA-600/2-81-122, July 1981.

An eighth completed effort (4) provided for the long-term testing of liner materials. Bag and tub testing of various membrane materials exposed to hazardous wastes was used. One of the objectives of this work was to assess the movement of organic contaminants through membrane liners. Permeability testing of various membrane liners was also attempted. Also, the study of membranes on rough surfaces was undertaken to determine their puncture resistance and creep over long periods of time. The results of work on this project will be used to update the technical resource document entitled "Lining of Waste Impoundment and Disposal Facilities," (SW-870) annually. This document is available from the Government Printing Office (055-000-00231-2).

A ninth ongoing effort (5) is concerned with evaluating innovative techniques for detecting and locating leaks in landfill liner systems. The three methods to be studies are Time Domain Reflectometry (TDR), the Acoustical Emission (AE) technique, and the Electrical Resistivity (ER) technique. These methods will be evaluated for their technical and economic feasibility at a surface impoundment that is presently being built and later at an actual liquid waste impoundment. A report entitled "Assessment of Innovative Techniques to Detect Waste Impoundment Liner Failings" has been reviewed and is expected to be published in FY 1983.

A tenth effort (5) is concerned with electrical resistivity techniques for locating liner leaks. Flexible membrane materials have been used as liners at landfills and surface impoundments to inhibit fluids from contaminating surrounding water resources. The primary objective of this task is to develop a method to detect and locate leak paths in membrane liners. The work consists of two-dimensional electrical modeling using a physical scale model. A system is underway to develop and demonstrate a search technique based on electrical measurement and leak-dependent signatures as observed in the model studies. Results have been published in several previous symposia proceedings. A final report entitled "Methods for Locating Liner Failures" will be published in 1983.

Pollutant Treatment

Chemical stabilization is achieved by incorporating the solid and liquid phases of a waste into a relatively inert matrix which exhibits increased physical strength and protects the components of the waste from dissolution by rainfall or by soil water. If this slows the rate of release of pollutants from the waste sufficiently and no serious stresses are exerted on the environment around the disposal site, then the wastes have been rendered essentially harmless and restrictions on siting will be minimal. A technical resource document entitled "Guide to the Disposal of Chemically Stabilized and Solidified Waste" (SW-872) reflects current state-of-the-art knowledge in the area of chemical fixation and is available from the Government Printing Office (055-000-00226-6).

The initial chemical fixation effort (4) which is completed relates to the transformation of wastes into an insoluble form to minimize leaching. The test program consists of investigating ten industrial waste streams in both the raw and fixed states. The waste streams are treated with at least one of seven separate fixation processes and subject to leaching and physical testing. The lab and field studies have been completed. The final results of these studies are reported in three reports entitled: 1) "Physical Properties and Leach Testing of Solidified/Stabilized are Gas Cleaning Waste," EPA 600/2-81-166; 2) "Physical Properties and Leach Testing of Solidified/Stabilized Industrial Wastes," (EPA 600/2-82-099) in press; and 3) "Field Investigation of Contaminant Loss From Chemically Stabilized Industrial Sludges," EPA 600/2-81-163.

A second completed effort (6) evaluated and verified several selected concentration techniques. Concentration/pretreatment schemes were selected for further development and subsequent bench scale verification with actual waste stream containing hazardous materials. Studies were carried out using various groundwaters which had been severely contaminated with organic compounds. Bench scale laboratory treatability studies, included activated carbon adsorption, resin adsorption, aerobic and anaerobic biological, and stripping. The results of this effort to date have been published in a report entitled "Concentration Technologies for Hazardous Aqueous Waste Treatment," EPA-600/2-81-019, January 1981. A technical resource document entitled "Management of Hazardous Waste Leachate" (SW-871) reflects the current state-of-the-art knowledge in leachate treatment and is available from the Government Printing Office (055-000-00224-0).

A third completed effort (5) relates to encapsulating processes for managing hazardous wastes. Techniques for encapsulating unconfined dry wastes are discussed in a report entitled "Development of a Polymeric Cementing and Encapsulating Process for Managing Hazardous Wastes," EPA-600/2-77-045, August 1977. Additional evaluations have been performed whereby containers of hazardous waste (i.e., 55 gallon drums) are placed in a fiberglass thermo-setting resin casing and covered with a high density polyethylene. The results of these evaluations have been published in three reports entitled "Securing Containerized Hazardous Wastes with Polyethylene Resin and Fiberglass Encapsulates," EPA-600/2-81-138, August 1981; "Securing Containerized Hazardous Wastes with Welded Polyethylene Encapsulates," EPA-600/2-81-139, August 1981; "Securing Containerized Hazardous Wastes by Encapsulation with Spray-On/Brush-On Resins," EPA-600/2-81-140, August 1981.

A fourth effort (4) was to determine how potentially useful sulfur-asphalt binder composites are for stabilization/solidification and disposal of toxic metal bearing wastes. Indications from work carried out on paving material suggest that both solid and aqueous inorganic as well as organic materials can be readily stabilized and solidified with binders comprised of sulfur-asphalt blends. This program was terminated and the report status is pending.

LANDFILL ALTERNATIVES

Due to the concern for environmental impact and economics, alternatives to waste disposal in landfills and by incineration have been proposed. In this regard, SHWRD is actively pursuing research related to surface impoundments and underground mines and their applicability for the disposal of wastes.

Surface Impoundments

The temporary, or permanant retention of liquid hazardous wastes in surface impoundments (i.e., pits, ponds, or lagoons) is an alternative to disposal in a landfill, which SHWRD is researching. Surface impoundments require special consideration to control vaporization and volatilization in the air.

An ongoing effort (6) is investigating mechanisms of chemical movement of pollutants from surface and near-surface impoundments into the air. Methods for estimating air emissions of hazardous chemicals from waste disposal sites are being developed. These methods include transport coefficients and conceptual models for those coefficients not available. Methods for controlling or reducing desorption from surface impoundments will be suggested.

A second completed effort (4) studied the potential for landfill collection drains to become clogged by chemical, physical and/or biological reactions. Individual landfill sites were studied to determine existence and nature of current or anticipated problems. Methods to remedy drain clogging were developed and refined.

A third completed effort (4) is concerned with reviewing current designs and construction practices for disposal facilities. Geotechnical parameters which should be tested, observed, and documented during construction, operation and closure of disposal facilities will be identified. Disposal facility construction sites will be selected for observation of the procedures used in verifying the geotechnical data. This project will lead to the development of a manual on state-of-the-art testing procedures. The final report entitled, "Geotechnical Quality Assurance in Construction of Disposal Facilities" should be available in September 1983.

UNDERGROUND MINES

The use of underground salt mines for the long-term controlled storage of non radioactive hazardous wastes has been shown to be promising as a result of studies by EPA and others and by the successful commercial operation of such a facility in West Germany since 1973.

A research program on characterization and containment of hazardous wastes for mine disposal was completed in 1977. This effort included determination of suitable mine locations, determining waste handling requirements, specifying operational techniques, and the preliminary design of a mine disposal system. This material was used to develop a feasibility report entitled, "Evaluation of Hazardous Waste Emplacement in Mined Openings," EPA 600/2-75-040, December 1975. Based upon the feasibility report, one or more candidate mines was selected for further evaluation and detailed economic design was completed. A report entitled, "Cost Assessment for the Emplacement of Hazardous Materials in a Salt Mine," EPA 600/2-77-215 was published in November 1977. An engineering plan for an initial pilot- scale operation was developed and a full- scale demonstration was planned in cooperation with a private firm, but never implemented. In FY 1983 an update of these studies of hazardous waste disposal into underground mines will be initiated.

UNCONTROLLED SITES/REMEDIAL ACTION

A completed study by OSW has identified incidence of water well contamination due to waste disposal sites. Seventy-five (75) to eighty-five (85) percent of all sites investigated are contaminating ground or surface waters. In order to determine the best practical technology and economical corrective measures to remedy these landfill leachate and gas pollution problems, a research effort has been initiated and completed (1) to provide local municipalities and users with the data necessary to make sound judgements of the selection of viable, in-situ, remedial action procedures and to give them an indication of the cost associated with such an action. This research effort is being pursued at a municipal refuse landfill site at Windham, Connecticut. The engineering feasibility study has been completed and a report entitled "Guidance Manual for Minimizing Pollution from Waste Disposal Sites," EPA-600/2-78-142, August 1978 has been published. This guidance document emphasizes remedial schemes or techniques for pollutant containment.

The field verification scheme installed and monitored at the Connecticut MSW site was a surface capping technique. This study is now completed and the results will be published in a final report entitled "Remediation of an Inoperative Municipal Waste Landfill - Windham Landfill, Windham, Connecticut." The report is expected to be available in late 1983.

A second completed effort (1 and 6) provides for a survey of ongoing and completed remedial action projects. Ten case study sites were selected and these sites visited and inspected for remedial action information. The results of this study are published in a report containing case study summary statistics of each of the sites investigated. The results of this completed effort were published in a final report entitled "Survey of On-Going and Completed Remedial Action Projects," EPA-600/2-81-246, September 1981. This survey will be periodically updated.

A third completed effort (6) is concerned with the assessment of barrel and drum reconditioning to determine environmental impact and to make recommendations for possible improvements in the reconditioning processes. Based on industry characterization and specific facility identification, two facilities were chosen for sampling and analysis efforts, which were monitored for air, land and water pollutant discharges. The results of this effort have been published in two reports entitled "Drum Reconditioning Process Optimization," EPA-600/2-81-233, September 1981 and "Barrel and Drum Reconditioning Industry Status Profile," EPA-600/2-81- 232, September 1981.

A fourth ongoing effort (2) is an investigation of the failure mechanisms and migration of industrial chemicals at a hazardous waste disposal site. The site has been closed and is under court order to be excavated for reburial elsewhere. During excavation of the landfill, the soil, facility, and waste conditions will be observed and samples will be collected. Work will also be conducted to determine to what extent external examination can identify problems with soil covers, to estimate service life of steel drums in landfills cells, and to correlate quick indicator tests (viscosity and filtration rates of leachate/clay mixtures) with soil permeability changes measured in the field. The final report on this project will include recommended improvements in design and operation of hazardous waste landfills.

A fifth effort (4) was concerned with evaluating the uses of geotextiles in stabilizing cover soils on landfills, act as drainage layers for gases and liquids, and act as a bedding for membrane barriers. This program studied available geotextiles and geotextile products, their engineering properties, sizes available (length, width, thickness), chemical resistance, seaming techniques, relative cost, life expectancy, and specific potential usage. This project included an initial assessment of problems at the municipal refuse landfill site in Windham, Connecticut, and recommendations for those remedial measures in which geotextiles could play a significant role. The final report entitled "Evaluaton of the Use of Geotextiles for Landfill Cover Systems" will be published late in 1983.

A sixth ongoing effort (4) is concerned with determining the feasibility of retrofitting existing surface impoundments with an effective membrane liner system. This study evaluates one or more technically feasible retrofit liner installation techniques including the applicable liner candidate materials. The work assesses under which physical and chemical in situ conditions the various techniques will have the greatest chance for success. External equipment requirements, safety, and economics as well as overall limitation are being determined. Pilot-scale and field verification will follow the technical and economical assessment. The data and procedures developed in this project will be used to update the existing TRD reports entitled "Lining of Waste Impoundment and Disposal Facilities" (SW-870) and "Closure of Hazardous Waste Surface Impoundments" (SW-873) available from the Government Printing Office (055-000-00227-4).

The seventh ongoing effort (7) is concerned with the assessment of remedial actions for uncontrolled hazardous waste disposal sites. Work on this project will lead to two distinct products. The first is to develop a detailed modeling program for site engineering assessment of remedial action alternatives at uncontrolled hazardous waste disposal sites. The second is to develop simplified desktop procedures for remedial action alternative assessment based on the detailed modeling program. Both products will describe the effectiveness and cost of remedial actions considering site factors and characterization of control technologies. The draft reports entitled "Remedial Action Technology Evaluation Models for Uncontrolled Hazardous Waste Site, Volume I: Detailed Models" and "Volume II: Simplified Desktop Models," respectively will be completed in FY 1983.

An eighth effort (7) is concerned with determining the effects of human safety and degree-of-hazard considerations on remedial action costs at uncontrolled hazardous waste sites. Cost components which are of a worker safety/degree-of-hazard nature will be identified. After identifying the component costs, specific cost figures will be determined. This information will be used to adjust total remedial action unit operation costs. The draft report entitled

"Cost Estimation Procedures for Remedial Action Technologies at Uncontrolled Hazardous Waste Sites," should be completed by July 1983.

A ninth completed effort (10) is the demonstration of a block displacement technique to seal off large blocks of contaminated earth. This was proposed to include a combination of drilling and fracturing techniques, displacement through injection of a specially formulated bentonite slurry, and ultimate placement of a low-permeability material across the bottom and around the sides of the block. This project provides data which demonstrates the feasibility of placing a horizontal stratum of pumpable material at a reasonable subsurface depth in a region of favorable geology. Problems associated with unknown geologic materials and the interrelationship with slurry injection technology were identified, serving as a significant data base upon which further practice can be more accurately predetermined. The field construction within this project has been completed and the report entitled "The Block Displacement Method Field Demonstration and Specifications" is undergoing final review for publication in 1983.

A tenth completed effort (8) has developed methods for classification of wastes by chemical and/or reactive properties and lays out a logical sequence of activities to determine the compatibility of two wastes. The key elements of the document are a compatibility chart and a flow diagram for its use. Therefore, simple and rapid field tests are needed to determine reactive properties, chemical class, generic name and results of mixing. Flame and solubility-reactivity testing procedures for the flow scheme were selected in September 1982. In addition, a workable redox test was established. A flow scheme and decision tree for liquids has also been established. The final report has been completed with anticipated publication by the end of FY 1983.

An eleventh ongoing effort (9) is concerned with the compatibility of various grouts with hazardous wastes. Data has been collected and is now being analyzed. Portland cement grouts, different percentage silicate base grouts, lignin base grouts, urea formaldehyde resin grouts, acrylamide grouts, and other types of grouts were examined. Also to be included will be a summary of procedures and tests recommended prior to selecting a grout for a particular hazardous waste site.

A twelfth completed effort (10) is concerned with the development of a handbook for slurry trench cutoff wall design, construction, and performance evaluation. Among the factors being tested is the use of different bentonites and their reactivity to hazardous waste and leachates. A summary of major cost elements will also be presented in the handbook. This Handbook will be printed as a Technical Transfer document in the Design Manual series published by EPA's Center for Environmental Research Information (CERI). Anticipated publication will be late 1983.

The purpose of a thirteenth effort (11) is to close a lagoon at the Louisiana Army Ammunitiions Plant near Shreveport, Louisiana. The lagoon contains wastewater from TNT manufacturing operations. State-of-the-art fixation techniques are being tested for the lagoon to insure that contaminants in the sludge will be immobilized. Also, processes that generated heat for the purpose of breaking the TNT ring are being tested. The results of this project are included in the Proceedings of the Ninth Annual Research Symposium.

The need for a practical compilation of evaluations and potential applications of various existing remedial action techniques has led to the development of a technical handbook. The handbook explains the nature of contamination at waste disposal sites and describes some of the remedial actions that can be applied for the clean-up of each contaminated medium. Remedial actions are designed to control, contain, treat or remove contaminants from uncontrolled hazardous waste sites. Remedial actions are divided into surface controls, groundwater controls, leachate controls, direct treatment methods, gas migration controls, techniques for contaminated water and sewer lines, and methods for contaminated sediment removal. The handbook is for industrial and governmental technical personnel involved with the clean-up of uncontrolled entitled "Cost Estimation Procedures for Remedial Action Technologies at Uncontrolled Hazardous Waste Sites," should be completed by July 1983.

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COST AND ECONOMIC ASSESSMENT

The use of market-oriented incentive (disincentive) mechanisms has received very little consideration for pollution control policy in the United States, particularly in the area of hazardous waste management. Economic theory suggests that incremental pricing of hazardous waste collection and disposal would reduce the waste generation rate and enhance resource recovery of recyclable materials.

An initial completed effort (7) developed a method to analyze the economic and social effects of alternative approaches to hazardous waste management. This method has been published in a report entitled "Socioeconomic Analysis of Hazardous Waste Management Alternatives: Methodology and Demonstration," EPA 600/5-81-001, July 1981.

A second completed effort (7) has resulted in a report entitled "Cost Comparison of Treatment and Disposal Alternatives for Hazardous Wastes," Volume I, EPA 600/2-80-188, February 1981 and Volume II, EPA 600/2-80-208, February 1981. Unit costs are estimated for sixteen treatment and five disposal techniques applicable to various hazardous wastes. Life cycle average unit costs are presented in both tabular and graphic form.

An ongoing third effort (7) analyzed unit operations cost data for long term remedial action programs at uncontrolled hazardous waste sites. The analysis included an outline of the process for costing remedial action unit operations and combining the unit operations to yield relative cost data for an entire remedial action scenario. The final report entitled "Costs of Remedial Response Actions at Uncontrolled Hazardous Waste Sites" should be available after FY 1983. A continuation effort is evaluating the effects of human safety and degree-of-hazard considerations on remedial action costs. This information will be incorporated into the report entitled, "Survey and Case Studies of Remedial Actions at Hazardous Waste Sites" which will be available in early 1984.

An ongoing fourth effort (7) is a cooperative agreement involving economic, legal and policy assessment related to CERCLA. The development of a legislative index of major implementation issues related to CERCLA has been completed and has been published by the Office of Emergency and Remedial Response. This report is entitled "Superfund; A Legislative History". Analysis of actual remedial action costs based on case histories is the major ongoing activity.

A fifth ongoing effort (7) provides direct technical assistance to State and Regional Office programs dealing with hazardous waste problems covered by CERCLA. It provides the assistance required to apply the best technological, yet cost-effective solutions to the problem sites and responsible agencies.

The principal objective of a sixth completed effort (7) is to develop an analytical framework for conducting cost-effectiveness and reliability evaluations of remedial options at uncontrolled hazardous waste sites. CERCLA requires that remedial actions to be implemented under Superfund must be cost-effective. This is defined in the National Contingency Plan as "the lowest cost alternative that is technologically feasible and reliable and which effectively mitigates and minimizes damage to and provides adequate protection of public health, welfare, or the environment". A methodology for making determinations of cost-effectiveness will be developed and a guidance document describing the application of the framework will be prepared, which can be used by EPA and state regulatory personnel to aid in consistent and comprehensive evaluation of the factors affecting reliability and cost-effectiveness of remedial actions. A draft report entitled "Guidelines for Conducting Cost-Effectiveness Evaluations at Uncontrolled Hazardous Waste Sites" has been prepared.

CONCLUSIONS

The laboratory and field research project efforts discussed here reflect the overall SHWRD effort in hazardous waste disposal research. The projects will be discussed in detail in the following papers. More information about a specific project or study can be obtained by contacting the project officer referenced in the text. Inquiries can also be directed to the Director, Solid and Hazardous Waste Research Division, Municipal Environmental Research Laboratory, U. S. Environmental Protection Agency, 26 West St. Clair Street, Cincinnati, Ohio 45268. Information will be provided with the understanding that it is from research in progress and the conclusions may change as techniques are improved and more complete data become available.

PROJECT OFFICERS

All the Project Officers can be contacted through the Solid and Hazardous Waste Research Division (SHWRD), whose address is shown above. The phone number is 513/684-7871.

1. Mr. Donald E. Sanning
2. Dr. Mike H. Roulier
3. Ms. Norma M. Lewis
4. Mr. Robert E. Landreth
5. Mr. Carlton C. Wiles
6. Mr. Stephen C. James
7. Mr. Douglas C. Ammon
8. Ms. Naomi P. Barkley
9. Mr. Herbert R. Pahren
10. Dr. Walter E. Grube, Jr.
11. Mr. Jonathan G. Herrmann

SUMMARY OF THE FIRST YEAR OF OPERATION

Hazardous Waste Research Center

Elvin J. Dantin
Hazardous Waste Research Center
Louisiana State University
Baton Rouge, Louisiana 70803

ABSTRACT

The Hazardous Waste Research Center, located at Louisiana State University, Baton Rouge, Louisiana, is one of eight research centers in the U.S. EPA Centers of Excellence program. This program, funded through the Agency's Research and Development Act of 1978, established institutional centers to focus on long-term, fundamental environmental research.

The organizational structure and the program areas of the Hazardous Waste Research Center are discussed, and the first year's accomplishments are highlighted.

The basic research focused on incineration, alternate methods of treatment/destruction, and chemical/materials interaction and stabilization. A summary of each research project is given. The current status of each project is also discussed.

In addition to the basic research efforts of the Hazardous Waste Research Center, two adjunct programs currently being pursued are discussed. A technology transfer program is being developed to communicate to industry, governmental agencies, academia and the public the advances being made through research and also to make available information on all aspects of hazardous waste. An applied research program is also established to work with industry to define and serve the immediate problem needs to industry.

BACKGROUND

In it's efforts to expand basic environmental research, the U.S. Environmental Protection Agency (EPA) established eight research centers, each assigned a topic of specialization. The Hazardous Waste Research Center (HWRC) is one of these centers. Louisiana State University was selected as the HWRC after a very competitive selection procedure, and was awarded a cooperative agreement on September 30, 1981.

CENTER'S STRUCTURE

The organizational structure of the Center, shown in Figures 1 and 2, exhibits the unique characteristics which contributed to LSU's selection for the location of the HWRC. The Center not only conducts basic research but has also established two adjunct programs to complement the basic research efforts. See Figure 3 for more detail on the adjunct programs. The funds to support the first year's activities of these adjunct programs have been received from industry.

A technology transfer program is being developed to communicate hazardous waste research results to industry, governmental agencies, academia, and the public, and to make available information on all aspects of hazardous waste. This program has a full-time person, supported by the State and industry, to assist in developing the program. An advisory group has been appointed to guide the program development.

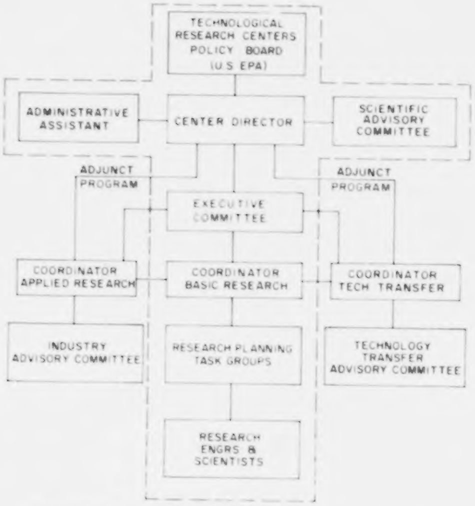
TECHNOLOGICAL RESEARCH CENTERS POLICY BOARD (U.S. EPA)
ADMINISTRATIVE ASSISTANT
CENTER DIRECTOR
SCIENTIFIC ADVISORY COMMITTEE
ADJUNCT PROGRAM
ADJUNCT PROGRAM
EXECUTIVE COMMITTEE
COORDINATOR APPLIED RESEARCH
COORDINATOR BASIC RESEARCH
COORDINATOR TECH TRANSFER
INDUSTRY ADVISORY COMMITTEE
RESEARCH PLANNING TASK GROUPS
TECHNOLOGY TRANSFER ADVISORY COMMITTEE
RESEARCH ENGRS & SCIENTISTS

FIGURE 1. ADMINISTRATIVE STRUCTURE

Also established is an applied research program to serve the immediate problem needs of industry. An Industry Advisory Committee was organized to assist in this needs identification process.

FIRST YEAR'S FUNCTIONING

Researchers from Louisiana State University (LSU) visited with U.S. EPA researchers from IERL, Cincinnati; RTP, North Carolina; MERL, Cincinnati; and Edison, New Jersey. From these meetings, suggested areas of research were proposed that would best fill the need in fundamental research in the hazardous waste area. An inventory of the faculty from LSU and scientists from Gulf South Research Institute (GSRI) was made to determine the expertise available to the Center as well as the interest of these individuals in the program. The interested participants met with the Project Officer of EPA, who presented an overall view of the Center's functions.

Coordinators were assigned to three research areas--incineration, alternate methods of treatment, and waste/materials interaction. The interested researchers met separately on several occasions to develop research studies within their research areas and preproposals were prepared in the three areas. Nineteen preproposals were submitted to the Executive Committee of the Center for evaluation.

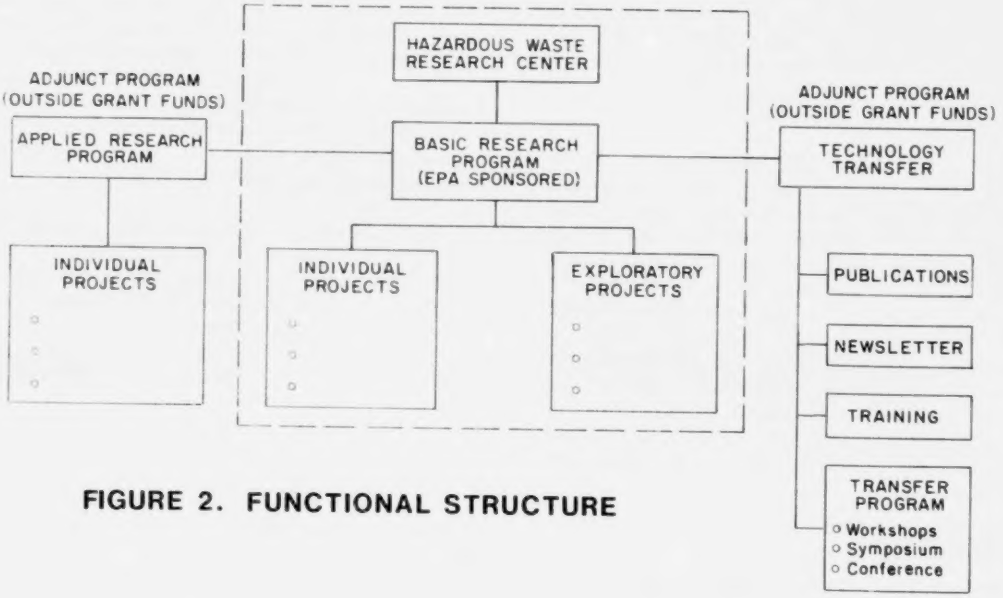
HAZARDOUS WASTE RESEARCH CENTER
ADJUNCT PROGRAM (OUTSIDE GRANT FUNDS)
APPLIED RESEARCH PROGRAM
BASIC RESEARCH PROGRAM (EPA SPONSORED)
ADJUNCT PROGRAM (OUTSIDE GRANT FUNDS)
TECHNOLOGY TRANSFER
INDIVIDUAL PROJECTS
INDIVIDUAL PROJECTS
EXPLORATORY PROJECTS
PUBLICATIONS
NEWSLETTER
TRAINING
TRANSFER PROGRAM
○ Workshops
○ Symposium
○ Conference

FIGURE 2. FUNCTIONAL STRUCTURE

APPLIED RESEARCH

FUNCTION:

TO ADDRESS COMMON INDUSTRY PROBLEMS NEEDING IMMEDIATE ATTENTION

TECHNOLOGY TRANSFER

FUNCTION:

1. TO COMMUNICATE TECHNICAL , STATE-OF-THE-ART INFORMATION TO INDUSTRY AND OTHERS PROFESSIONALLY INVOLVED IN HAZARDOUS WASTE
2. TO DEVELOP AN INFORMATION CENTER THROUGH WHICH GENERAL INFORMATIOM IS COLLECTED, ORGANIZED, MADE ACCESSABLE AND/OR COMMUNICATED TO ANY PUBLIC OR PROFESSIONAL USER

FIGURE 3. FUNCTIONS OF THE TWO ADJUNCT NON-EPA FUNDED PROGRAMS

As a result of the Executive Committee's evaluation, eleven preproposals were submitted to the Policy Board of EPA for their review and approval at the first meeting of the Board on December 8-9, 1981, at LSU. At this meeting the Policy Board also approved the three focus areas of research for the Center. Specifically, the Policy Board of HWRC approved three research projects in incineration, two research projects and one planning study in alternate methods of treatment, and two research projects and one planning study in waste/material interaction. A total of nine projects was approved.

Upon acceptance of the Year 01 programs by the Policy Board, initial steps were taken toward establishing the Scientific Advisory Committee (SAC). The relationship of the SAC to the overall functioning of the Center can be seen by referring back to Figure 1. At the Policy Board meeting held in Chicago, June 10, 1982, a partial list of candidates was presented to the Policy Board for approval. There are now eleven members appointed to the Committee. Membership includes representatives from U.S. EPA, industry, and academic communities.

Basic Research

During the first year of activity, seven research projects and two planning studies were identified and funded. Of the seven research projects approved, all were designed as multi-year projects. The results of the first year's research efforts have been reviewed by SAC and recommendations for continuation, based on the project's progress for the first year, have been made to the Policy Board. The two planning studies were terminated at the end of the first year.

The title, principal investiator(s), and period of support, together with a brief statement of objectives for each funded research project during the first year are given below. Although the first year funding period for the cooperative agreement was November 15, 1981 through November 14, 1982, delays in program evaluation and funding caused a delay in the starting date for most projects.

1. Title: Destructability of Pure Hazardous Waste Compounds in a Laboratory Flame Environment
   Principal Investigator: V. A. Cundy, Assistant Professor of Mechanical Engineering
   Period of Support: 15 January 1982 - 14 November 1982

The objective of this study is to obtain the fundamental combustion kinetic data associated with the destruction of chlorinated hydrocarbon wastes. A flame burner system will be designed and constructed to perform this study. Samples of gas will be obtained through the flame produced by the waste fuel providing concentration profiles. This data, along with temperature profiles and flame velocity information, will then be utilized to project the fundamental chemical kinetic data occurring. Such information will provide more exact details concerning the transformation of the waste material to less toxic substances as it progresses through the flame.

This project has been approved for continuation for the second year.

2. Title: The Effects of Physical and Thermodynamic Properties on the Combustion of Liquid Wastes
Principal Investigator: A. M. Sterling, Professor of Chemical Engineering
Period of Support: 15 January 1982 - 14 November 1982

The purpose of this project is to investigate the atomization of liquid wastes. In contrast to furnaces that burn fuels of known properties, liquid-waste incinerators will be required to burn materials with a wide variation in properties. In order to tailor the operating parameters of the furnace to achieve optimum combustion efficiency, the effect of the atomization process on operating parameters must be known. The first step in the project will be to develop an instrument that can be used to measure spray characteristics. The instrument will consist of a laser beam and associated lenses and photo detectors, and will be able to measure both the size and velocity of droplets at various locations throughout the spray. The effect of liquid properties and the operating parameters of the nozzle on the spray characteristics can therefore be measured and correlated.

The proposal has been completely rewritten in close collaboration with the Scientific Advisory Committee and is being evaluate by the entire Incineration Combustion subgroup of the SAC. Recommendation from SAC will be forthcoming.

3. Title: Incinerability Characteristics of Selected Hazardous Waste Materials
Principal Investigator: R. A. Matula, Professor of Mechanical Engineering
Period of Support: 15 January 1982 - 14 November 1982

The objective of this study is to develop a better understanding of the combustibility or incinerability characteristics, as reflected by the combustibility or incinerability characteristics, as reflected by chemical and/or kinetic properties, of a selected group of pure hazardous waste compounds. Presently, experimental work is being carried out to determine if either infrared emission from carbon monoxide (CO) or carbon dioxide (CO_2) can be utilized as an effective measure of ignition delay times for chlorinated hydrocarbon/oxygen systems. In addition, analytical models for the combustion of CCl_4 are being developed in order to obtain a better understanding of the reactions important in the ignition and oxidation of chlorinated hydrocarbons.

This project has been approved for continuation for the second year.

4. Title: Destruction of Hazardous Organic Leachates by Photolytic Ozonation
Principal Investigators: D. Roy, Assistant Professor of Civil Engineering; M. E. Tittlebaum, Assistant Professor of Civil Engineering
Period of Support: 15 January 1982 - 14 November 1982

The major objective of this research is to obtain information on the kinetics and mechanism of destruction of hazardous organic wastes by photolytic ozonation. Application of the photolytic ozonation process for complete destruction as well as for enhancement of biodegradability of hazardous wastes and leachates will be investigated. Based on these findings an engineering design approach will be developed.

The proposal is being revised with major input from SAC and the Policy Board, and will be re-evaluated by SAC. Recommendations will be forthcoming.

5. Title: Rate Mechanisms in the Supercritical Extraction of Organics from Solid Hazardous Wastes
Principal Investigators: F. C. Knopf, Assistant Pro-

fessor of Chemical Engineering; E. McLaughlin, Professor of Chemical Engineering; R. G. Rice, Professor of Chemical Engineering
Period of Support: 15 January 1982 - 14 November 1982

The removal of organic hazardous wastes from contaminated soil due to chemical spill is the concern of this project. In supercritical extraction technology, a simple gas such as carbon dioxide at high pressure and moderate temperatures, is contacted with the contaminated soil and the organic waste is leached out into this high pressure gas in which it freely dissolves. The gas can then be vented off into a tank where, if the pressure is reduced, the hazardous waste falls to the bottom of the tank and the pure carbon dioxide gas comes off the top. The gas is returned to a compressor which compresses it up to high pressure. It is again returned to the contact tank to remove more waste from the soil.

The proposal has been revised with major input from SAC, Policy Board, and external reviewers. SAC members and external reviewers are evaluating this proposal. Recommendations will be forthcoming.

6. Title: Leachate Effects on Structural Stability and Hydraulic Conductivity
Principal Investigator: Y. Acar, Assistant Professor of Civil Engineering; R. E. Ferrell, Professor and Chairman of Geology; S. D. Field, Assistant Professor of Civil Engineering
Period of Support: 15 January 1982 - 14 November 1982

This research addresses the question of what is the long-term fate of hazardous materials being currently disposed of in landfills. What happens to wastes buried in such sites? Over long periods of time (decades to centuries) it is known that the wastes will tend to migrate through the clay liners at very slow rates. At the same time the wastes are subject to absorbtion on soil particles and degradation. This study investigates the rates of decay of specific wastes (p-chloro-m-cresol, arocolor 1254, 2-4-dinitrotolune, and 1,2-dichlorobenzene). This information will assist in the analysis of whether these specific wastes can be safely buried in the future.

A new proposal is being prepared in close collaboration with SAC members.

The Hazardous Waste Research Center also supported two research planning studies in the first year that will not be continued in the second year. The intent of the planning studies was to review existing information in specific subject areas and identify research needs. The information from these planning studies would be used to prepare research projects to fill the voids which exist in the fundamental subject areas.

1. Title: An Assessment of the Technical Feasibility of Stabilization of Hazardous Organic Liquid Wastes and Sludges
Principal Investigators: R. K. Seals, Professor and Chairman of Civil Engineering; M. E. Tittlebaum, Assistant Professor of Civil Engineering
Period of Support: 15 January 1982 - 14 November 1982

The objectives of this project are to determine the present state-of-the-art of stabilization of hazardous organic liquid wastes and sludges, and to identify the principal types and estimated quantities of these wastes and sludges. Potential bonding mechanisms between organic wastes and candidate stabilization materials and mechanisms that interfere with stabilization processes will be identified. The potential use of waste residuals in stabilization processes needs to be determined. Pretreatment techniques to enhance the stabilization of organic waste need to be identified, and a program to evaluate the performance of these stabilization techniques needs to be developed.

The final report for the first year has been completed and is being reviewed by SAC and the Policy Board. A research proposal based on these findings is being reviewed by SAC, and recommendations will be forthcoming.

2. Title: Novel Treatment Techniques for Soils Contaminated with Hazardous Substances
Principal Investigators: D. P. Harrison, Professor of Chemical Engineering; D. M. Wetzel, Assistant Professor of Chemical Engineering
Period of Support: 15 January 1982 - 14 November 1982

This study will survey possible alternate treatment/destruction methods to identify those which appear to be most promising in terms of ultimate destruction capability, cost effectiveness, and potential applicability. Key research needs for each of the most promising methods will be identified and used to guide the long-term research effort in this area.

The final report for the first year has been completed and is being reviewed by SAC and the Policy Board. A research proposal based on these findings is being reviewed by SAC, and recommendations will be forthcoming.

Applied Research

The faculty coordinator for the applied research program met periodically with the Industry Advisory Committee (IAC) to identify areas of concern as well as the alternative approaches to solving the problems. The active participation and the serious concern of the members of the IAC was evident in the first year.

Technology Transfer

In technology transfer's first year, many tasks, as program planning, Center support functions, numerous publications and other activities, were performed. The publications are described in the following section. Program planning focused on activities to benefit industry, government and academic researchers. An assessment of the support capabilities for research in hazardous waste by the LSU Library was begun. Efforts to strengthen this support capability are planned. Members for the Technology Transfer Advisory Committee were selected.

PUBLICATIONS

Through the Technology Transfer program of the HWRC, publications have been prepared that will be used to increase industry and community awareness of the purpose and functioning of the Center. Magazine articles to appear in the LSU College of Engineering Engineering News and the newsletter, Water Currents, were written to publicize the existence and function of the Center. Currently in printing are a brochure and a newsletter.

Another publication was the Proceedings of the Symposium and Workshop on Hazardous Waste Management: Protection of Water Resources. The Symposium, held in November 1982 at LSU, was organized to present the important issues in hazardous waste management. The Symposium was followed by a workshop conducted to define research needs in the hazardous waste area.

The following technical publications have resulted from the HWRC research studies.

1. "Destruction of Hazardous Wastes by Photolytic Ozonation," D. Roy, M. E. Tittlebaum and R. Knox. Presented at the Louisiana Conference on Water Supply, Sewage, & Industrial Wastes sponsored by the Louisiana Water Pollution Control Association in March, 1982.
2. "Comparison of Exact and Approximate Solutions of Transient Response for Leaching by SCF in CSTR." F. Carl Knopf, Edward McLaughlin and Richard G. Rice. Chemical Engineering Communications.
3. "A Quantitative Approach to the Long-Term Effectiveness of Landfilling of Organic Hazardous Wastes." Ron Malone and Michelle Frey. To be submitted to Journal of Hazardous Materials.
4. "Organic Leachate Effects on Hydraulic Conductivity of Compacted Kaolinite." Hamidon, Scott, Y. Acar and S. Field. To be presented at the International Symposium on Impermeable Barriers

for Soil and Rock, and later published in an ASTM Special Technical Publication.

5. "Pure Organic Solvent Effects on the Fabric of Compacted Clay." Olivieri, Y. Acar and S. Field. To be presented at the International Symposium on Impermeable Barriers for Soil and Rock. Later to be published in an ASTM Special Technical Publication.

In addition, final reports have been prepared for the two research planning studies.

FUTURE PLANS

Two new research proposals have resulted from the planning studies. In addition, eight new research proposals have been submitted to the Center for evaluation. The two proposals resulting from the planning studies and two of the new proposals are being evaluated by the SAC and Policy Board, and, if approved and funds become available, will be included in the second year of the Center's program.

With support from industry and the State, the Center will sponsor a symposium and several short courses in 1983 and 1984. The technology transfer program will maintain a depository of current informtion and develop materials for transferring information to professionals as well as lay people. The quarterly publication of a newsletter as well as numerous other publications are planned.

A more active participation and rapport with industry is anticipated as the Center develops its applied research program in hazardous waste.

The future of the Center will depend on the support of U.S. EPA to continue the fundamental research program. The technology transfer and applied research program are the necessary added involvement to develop the Center into a Comprehensive Center of Excellence in Hazardous Waste Research.

A MODEL FOR HYDROLOGIC EVALUATION OF LANDFILL PERFORMANCE

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ABSTRACT

The HELP model is an interactive computer-based model designed for use by nonprogrammers to evaluate the probable hydrologic performance of existing or proposed landfill designs. The model simulates runoff, infiltration, evapotranspiration, lateral subsurface flow, and percolation using accepted theoretical relationships and water routing techniques. Outputs from the model include all aspects of the hydrologic cycle, with particular emphasis on leachate production and percolation losses. The hydrologic model is interfaced directly with precipitation and temperature files from representative areas around the United States and has default parameter values for simulations of most landfill designs. The theoretical development of the HELP model and its application to evaluation of probable landfill performance is discussed.

INTRODUCTION

The Hydrologic Evaluation of Landfill Performance (HELP) model was developed to assist in the design of waste disposal sites and in the evaluation of the environmental impact of existing waste disposal sites. The HELP model is an improved and extended version of the Hydrologic Simulation model for estimating percolation at Solid Waste Disposal Sites (HSSWDS) (1,2), that was developed for the U.S. Environmental Protection Agency. The resulting model is a quasi-two-dimensional, deterministic model that computes the daily water budget for a landfill design, considering percolation through successive horizontal layers and lateral drainage from above sloping barrier layers. The HELP model is based on accepted, but simplified, soil physical theory using parameters for which values are available from the landfill design specifications or from reports in the hydrology literature.

The HELP model is implemented, as was HSSWDS, with a full set of default soil characteristics and default climatologic data for representative locations in all parts of the country. Therefore, the prospective model user can use HELP by specifying only the sequence of soil, waste, and barrier layers, with layer dimensions and layer textures.

The model is implemented for use in a conversational mode so that the user receives his output at a computer terminal. A question and answer format is used so that no programming experience is necessary to run the HELP program.

MODEL STRUCTURE

The overall configuration of the HELP model is shown in Figure 1. The user specifies the sequence and characteristics of the layers in the model. Any of the layers

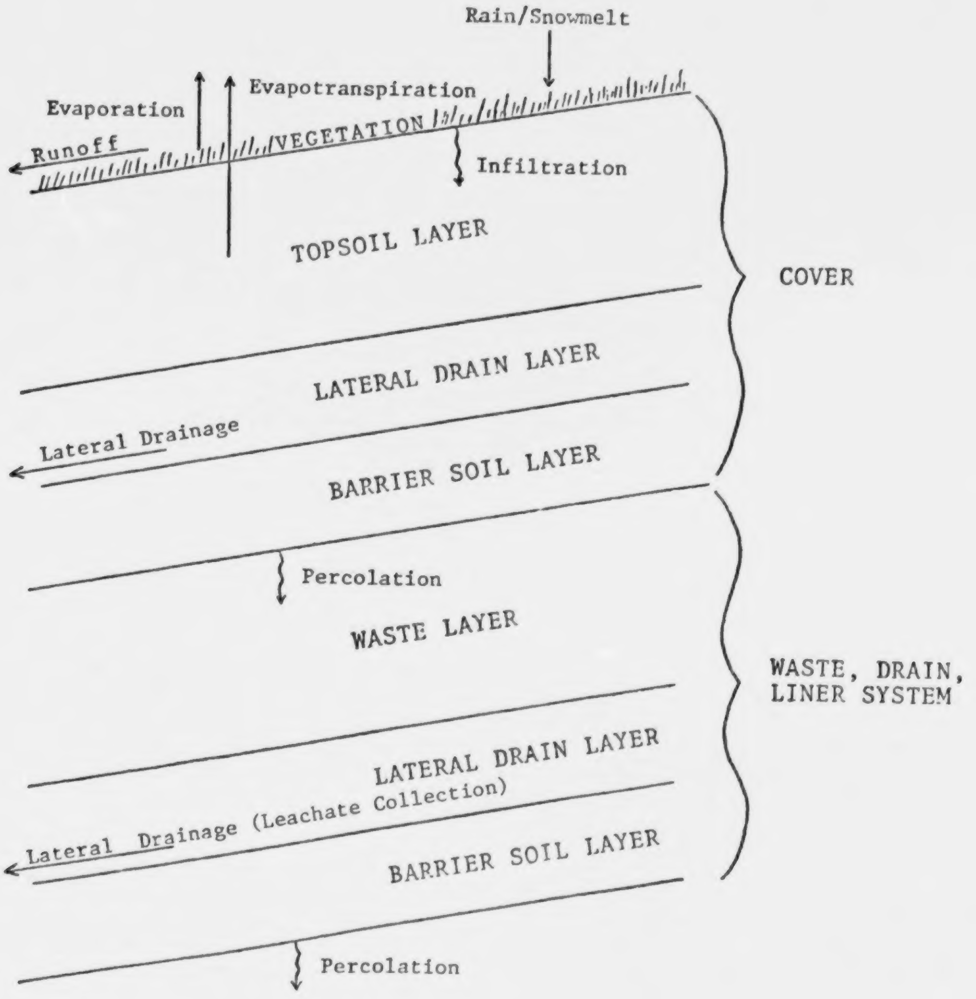
Rain/Snowmelt
Evaporation
Evapotranspiration
Runoff
VEGETATION
Infiltration
TOPSOIL LAYER
COVER
LATERAL DRAIN LAYER
Lateral Drainage
BARRIER SOIL LAYER
Percolation
WASTE LAYER
WASTE, DRAIN, LINER SYSTEM
LATERAL DRAIN LAYER
Lateral Drainage (Leachate Collection)
BARRIER SOIL LAYER
Percolation

Figure 1. Configuration of HELP model.

shown in Figure 1 may be omitted, or additional waste cells may be added below the one shown. An open landfill, prior to sealing, may be simulated by omitting the layers of the cover, such that the uppermost layer is a waste layer.

The amount of moisture that enters the topsoil layer is determined by a daily infiltration submodel that considers the amount of antecedent moisture and the density of vegetation on the surface. Infiltrated water is routed through conceptual soil segments to the barrier layer where it is subject to evapotranspiration demand and gravity drainage. Drainage may occur by vertical percolation or lateral subsurface flow. The input to layers below the cover is the amount computed as percolation through the barrier layer. Multiple barrier layers and lateral drainage layers are possible.

The HELP model computes runoff by the Soil Conservation Service (SCS) curve number method (3). Percolation is computed by Darcy's Law, modified for unsaturated flow (4). Lateral flow is computed by a linearization of the Boussinesq equation and evapotranspiration is determined by a method developed by Ritchie (5). The vertical percolation and evapotranspiration components of the HELP model originated with the CREAMS (6) program. The development presented here, however, reflects a significant advance beyond the CREAMS model in both of these areas. Each of these model components will be discussed in detail below.

Runoff and Infiltration

The SCS curve number technique (3) as first implemented in the CREAMS model, was selected as a model to partition incoming rainfall or snowmelt between runoff and infiltration in HELP. This technique was selected because:

1. It is a well-established procedure and appropriate values for the curve number can be assigned without great difficulty,

2. It provides a computationally efficient procedure for estimating daily runoff values from daily precipitation, and

3. A wide variety of surface vegetative cover densities can be simulated.

The SCS equation relates daily runoff volume, Q, to daily precipitation, P, and a watershed retention parameter, S, as follows:

$$Q = \frac{(P-0.2S)^2}{(P+0.8S)} \qquad (1)$$

where, Q, P, and S are in inches.

The retention parameter, S, is a nonlinear function of soil wetness and vegetative cover density. It has been related to a series of empirical curves developed by SCS. An appropriate curve can be selected from the SCS manual (3) to match the desired surface cover for a landfill. The curve number, CN, is related to the retention parameter as:

$$S = \frac{1000}{CN} - 10 \qquad (2)$$

The actual value of S for any time during a simulation period is computed by the procedure described in CREAMS (6):

$$S = S_{max}\left[1 - \frac{SM - WP}{UL - WP}\right] \qquad (3)$$

where S_{max} = retention parameter value for a dry antecedent condition

SM = a depth weighted estimate of soil moisture (dimensionless)

UL = upper limit of soil water storage or total porosity of the soil (dimensionless)

WP = the lower limit of soil water storage or wilting point. (dimensionless)

To account for the nonuniform distribution of moisture in the soil profile, a weighting function which gives greater weight to moisture near the surface is used. The soil profile in the evaporative zone is divided into seven segments. These soil segments are used in the moisture routing scheme, and their soil moistures are averaged to compute the effective soil moisture.

Soil segments vary in thickness as follows: the uppermost segment has a thickness equal to 1/36 times the lesser of the depth from the surface to the barrier layer and the depth of the evaporative zone; the second layer has thickness equal to 5/36 of the profile, and the remaining five segments each have thickness equal to one-sixth of the profile. The depth-weighted retention parameter is computed as:

$$S = S_{max}\left[1 - \sum_{j=1}^{7} W_j\left(\frac{SM_j - WP_j}{UL_j - WP_j}\right)\right] \qquad (4)$$

where W_j = weighting factor for segment j

SM_j = soil moisture content of segment j

UL_j = upper limit of soil moisture content of segment j

WP_j = wilting point of moisture content of segment j

The weighting factors are identical to those used in CREAMS (3): for segments 1 through 7, these weighting factors are 0.111, 0.397, 0.254, 0.127, 0.063, 0.032, and 0.016, respectively.

The value of S_{max} in Equation 3 corresponds to the retention parameter for dry antecedent moisture conditions (AMC-I). The curve number for AMC-I, CN_I, is computed from the average curve number CN_{II} as follows:

$$CN_I = -16.91 + 1.348\ CN_{II} - 0.01379\ CN_{II}^2 + 0.0001177\ CN_{II}^3 \qquad (5)$$

Infiltration is computed as the difference between the daily precipitation and runoff computed by Equation 1, minus the daily surface evaporation. If the mean daily temperature is below 32°F, the precipitation is stored on the surface as snow and does not contribute to infiltration or runoff until the mean daily temperature rises above 32°F. The amount of melted snow is added to precipitation for use in Equation 1.

The amount of snowmelt on day i is computed as follows:

$$M_i = 0 \text{ for } T_i \leq 32°F \text{ or } SNO_{i-1} = 0$$

$$M_i = 0.06\ (T_i - 32) \text{ for } T_i > 32°F \text{ and } SNO_{i-1} > 0.06\ T_i \qquad (6)$$

$$M_i = SNO_{i-1} \text{ for } T_i > 32°F \text{ and } SNO_{i-1} < 0.06\ T_i,$$

where M_i = amount of snow melted on day i, inches

T_i = mean temperature on day i, °F

SNO_{i-1} = amount of snow water on surface at the end of day i-1, inches.

Evapotranspiration

The evapotranspiration (ET) from a landfill cover is a function of the energy available, the vegetation, the soil transmissivity, and the soil moisture content. The potential ET is computed in HELP by a modified Penman method as described by Ritchie (5) and used in CREAMS (6):

$$E_o = \frac{1.28\ A\ H}{A + 0.68} \qquad (7)$$

where E_o = potential ET, mm

A = slope of saturation vapor pressure

H = net solar radiation, langleys

Daily mean temperatures and solar radiation values are obtained by fitting a simple harmonic curve to the monthly mean values by Fourier analysis. The resulting equation is evaluated for each day of the simulation.

The daily potential ET is applied first to any free water available on the surface, thereby reducing the computed infiltration or the amount of snow on the surface. Any ET demand in excess of free surface water is exerted on the soil column for direct soil evaporation and evapotranspiration through the surface vegetation.

Soil evaporation proceeds in two stages: stage one, where evaporation is controlled by atmospheric demand and stage two where evaporation is limited by soil transmissivity. The potential soil evaporation is computed as:

$$ES_o = E_o \exp\ (-0.4\ LAI) \qquad (8)$$

where ES_o = potential soil evaporation, mm

E_o = potential ET, mm

LAI = leaf area index (on scale of 0 to 3)

During the nongrowing season, LAI in Equation 8 is replaced by a winter cover factor (WCF) which varies between 0 and 1.8 depending on the density of dead or dormant vegetation.

In stage one evaporation, soil evaporation is equal to the potential soil evaporation ES_o. An upper limit to the amount of stage one evaporation is computed as:

$$U = 9(a_s - 3)^{0.42} \qquad (9)$$

where U = the upper limit for stage one evaporation in mm

a_s = soil transmissivity parameter for evaporation in $(\text{mm/day})^{1/2}$

When the accumulated stage one evaporation less the infiltration exceeds the upper limit, U, any further soil evaporation proceeds by the following equation:

$$ES_2 = a_s \left[t^{1/2} - (t-1)^{1/2}\right]$$

where ES_2 = stage two soil evaporation, mm

t = days since stage one ended

Whenever the infiltration exceeds the cumulative evapotranspiration less the upper limit for stage one evaporation, evaporation reverts to the stage one process.

Potential plant transpiration is computed as

$$EP_o = \frac{E_o LAI}{3} \quad (10)$$

The potential ET may be satisfied entirely by evaporation from free water, from stage one soil evaporation, or from stage two soil evaporation. If there is remaining atmospheric demand after these sources of ET have been exhausted, the demand will be satisfied by plant ET to a maximum of EP_o. The actual ET varies as a function of soil moisture and atmospheric demand as shown by Shanholtz and Lillard (7), Saxton et al. (8), and Sudar et al. (9). The following relationship was developed from ET-rate curves for no-till corn presented by Shanholtz and Lillard (7):

$$EP = EPD \left[1.20 - \frac{EPD}{6.35} + \left(\frac{SM-WP}{FC-WP}\right)\right] \quad (11)$$

where EP = actual plant ET, mm

EPD = actual plant ET demand, mm

$= E_o - ES - ESS$

if $EP_o > E_o - ES - ESS$

$= EP_o$

if $EP_o \leq E_o - ES - ESS$

ES = actual soil evaporation, mm

ESS = that portion of the total evapotranspiration met from precipitation or snow, mm

SM = soil moisture content, vol/vol

WP = wilting point moisture content of the soil, vol/vol

FC = field capacity of the soil, vol/vol

The soil moisture, wilting point, and field capacity values used in Equation 11 are depth-weighted using the same weighting coefficients used for computation of the retention factor used in Equation 1.

The rate of change in leaf area index (DLAI) during different parts of the year is computed from 13 LAI values that represent values for different dates from a year in which no severe droughts occurred. The appropriate values of DLAI are used to compute LAI on a daily basis throughout the year. When drought occurs and the weighted soil moisture approaches the wilting point, no increase in LAI occurs.

The total ET is the sum of free surface evaporation, stage one and stage two soil evaporation, and plant ET. The plant ET is distributed to the conceptual segments of the soil profile using the same weighting factors used previously to estimate the average soil moisture. As each segment is depleted to wilting point, the next lower segment is subject to an additional ET demand that is equal to the remaining plant ET of the above segment. The result of this procedure is that water is drawn rapidly from the upper segments of the profile, then moves to deeper segments as the upper segments are depleted. As the ET demand extends to deeper segments, the efficiency of moisture withdrawal is reduced by the segments weighting factor. The HELP model simulates ET moisture withdrawal to a maximal depth of 120 cm, but the efficiency of moisture withdrawal below 45 cm is very low. This distribution of ET demand through the soil profile is consistent with data presented by Saxton et al. (8).

Vertical Moisture Flow

The vertical flow submodel is depicted in Figure 2 as it is implemented for simulation of moisture movement in a landfill cover. When applied to an open landfill or to a landfill with multiple barrier layers, soil or waste layers below the barrier are represented by fewer segments.

The input to the vertical flow model is the infiltration estimate less any surface evaporation. Output from the model is divided between lateral flow and vertical percolation through the barrier layer. Drainable moisture, that in excess of field capacity, is transferred through the profile by storage routing procedures.

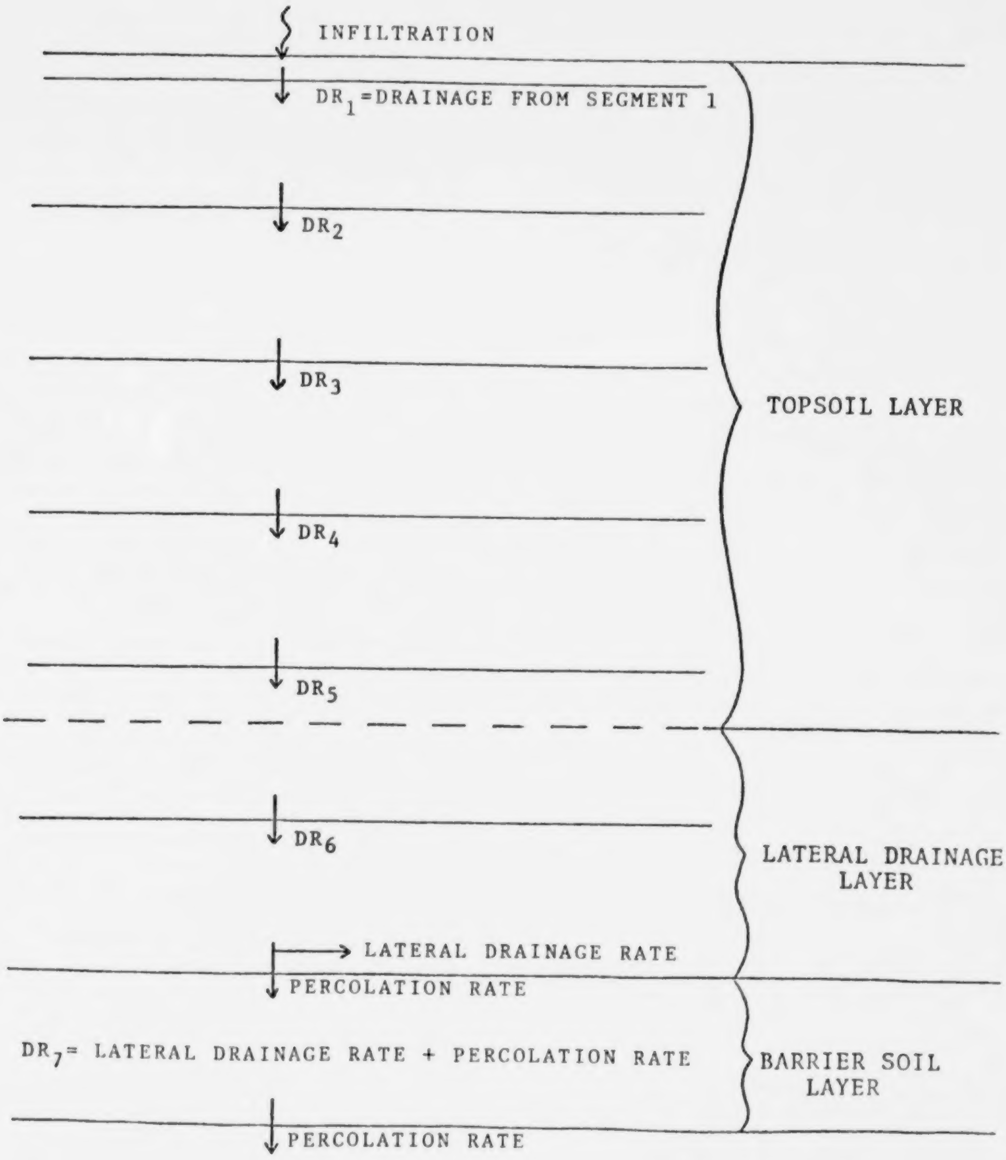
INFILTRATION
DR1 =DRAINAGE FROM SEGMENT 1
DR2
DR3
TOPSOIL LAYER
DR4
DR5
DR6
LATERAL DRAINAGE LAYER
LATERAL DRAINAGE RATE
PERCOLATION RATE
DR7= LATERAL DRAINAGE RATE + PERCOLATION RATE
BARRIER SOIL LAYER
PERCOLATION RATE

Figure 2. Vertical flow submodel for landfill cover.

The profile of the landfill cover is generally assumed to consist of eight segments, where the bottom of segment seven is the upper boundary of the barrier layer. If the profile consists of several layers, as shown in Figure 2, the layer properties are assigned to corresponding model segments. Where segment and layer boundaries do not coincide, the segment properties (conductivity, porosity, etc.) are computed as thickness-weighted averages of the two layers represented. In this way a layered profile consisting of loam over sand may be modeled as having a gradual change in soil properties.

Below the landfill cover, the waste and drainage layers may each be modeled as a single soil segment. The input to layers below a barrier is the amount of water that percolates through the barrier above. The barrier layer itself is always modeled as being separate from the rest of the profile.

Storage routing through segments of the model consists of simultaneous solution of Darcy's Law and an equation of continuity. Darcy's Law is represented as:

$$q = K\frac{dh}{dl} \qquad (12)$$

where q = rate of vertical flow, inches/day

K = hydraulic conductivity, inches/day

h = gravitational head, inches

l = length in the direction of flow, inches

Free outfall is assumed from each segment such that dh/dl may be set equal to unity, and q is equal to the hydraulic conductivity. This assumption is acceptable only if the conductivity of the profile is constant or increases with depth. Because this assumption is not met at the interface between the seventh segment and the barrier layer, a different procedure is employed there.

The rate of vertical moisture flow in soil varies with soil moisture content. When the soil is fully saturated, the flow rate is equal to the saturated hydraulic conductivity, and when the moisture content is reduced to field capacity, the flow rate is zero. In the HELP model the hydraulic conductivity is taken to be a linear function of soil moisture:

$$k_u = k_s\left(\frac{SM-FC}{UL-FC}\right) \qquad (13)$$

where k_u = unsaturated hydraulic conductivity, inches/day

k_s = saturated hydraulic conductivity, inches/day

SM = soil moisture content, vol/vol

FC = soil moisture content at field capacity, vol/vol

UL = total porosity or the soil moisture content at saturation, vol/vol

The continuity equation is written to represent the midpoint of the routing time interval as:

$$\Delta S = \frac{I_1 + I_2}{2} - \frac{O_1 + O_2}{2} \qquad (14)$$

where ΔS is the change in storage during the time interval,

I_1 and I_2 are inflows to storage at the beginning and end of the time interval, and

O_1 and O_2 are outflows from storage at the beginning and end of the time interval.

The first term on the right hand side of Equation 14 represents the average inflow, and the second term represents the average outflow. The inflow to the uppermost segment is infiltration; inflow to other segments is percolation from the above segment. Outflows are by gravity drainage or ET.

Rearranging Equation 14, the change in storage (of a segment) may be written as the sum of one-half the net drainage from the previous time interval and one-half the net drainage at the end of the current time interval. Therefore:

$$SM_i = SM_{i-1} + 1/2\ NDR_i + 1/2\ NDR_{i-1} \qquad (15)$$

where SM_i = soil moisture at the end of the current time interval,

SM_{i-1} = soil moisture at the end of the previous time interval,

NDR = net drainage,

and

$$NDR_i(j) = \left[DR_i(j-1) - DR_i(j) - ET_i(j)\right]\Delta t \qquad (16)$$

where j = segment number,

i = time,

DR = drainage rate,

Δt = the time interval, and

ET = evapotranspiration rate.

The drainage rate from a segment is written as:

$$DR_i = k_s\left[\frac{\frac{SM_i + SM_{i-1}}{2} - FC}{UL - FC}\right] \qquad (17)$$

and Equations 17 and 15 may be solved simultaneously, knowing SM_{i-1} from the previous time interval. The resulting drainage from segment j is:

$$DR_i(j) = 2k_s(j)\left[SM_{i-1}(j-1) + 1/2\ NDR_{i-1}(j) + 1/2\ DR_i(j-1)\,\Delta t - 1/2\ ET_i(j)\,\Delta t - FC(j)\right] \Big/ \left[2(UL(j) - FC(j)) + k_s(j)\,\Delta t\right] \qquad (18)$$

The routing proceeds from the top segment, where incoming drainage is infiltration (rainfall less surface evaporation), to the seventh segment where the drainage out is divided between percolation through the barrier layer and lateral drainage above the barrier layer.

Percolation

An accurate estimate of percolation rate cannot be obtained using the routing procedure described in the vertical flow submodel because of the discontinuity at the interface with the barrier layer. Percolation is modeled as Darcian flow where the drainage rate is computed as:

$$q_p = k_c\left(\frac{TH + T_c}{T_c}\right) \qquad (19)$$

where q_p = the rate of percolation through the barrier

TH = the total head in the profile above the barrier layer,

T_c = the thickness of the barrier, and

k_c = the saturated hydraulic conductivity of the barrier.

To reduce complexity of the percolation model, the drainable porosity of the barrier is considered negligible. This assumption has the effect that drainage stops as soon as there is no head above the barrier. In fact, if the barrier is a typical clay, it would continue to drain at a very low rate until the drainable water is depleted. If the drainable porosity of the clay were one percent and the thickness of the barrier were 60 cm, 0.6 cm of water could drain from the barrier after all drainable water was removed from the profile above the barrier. Because the hydraulic conductivity of clay is very low (on the order of 10^{-7} cm/sec), it would require several months to deplete the drainable water from the clay. Further, it must be considered that the percolation of water from the soil profile into the drainable volume of the clay will also proceed at a slow rate due to the low hydraulic conductivity of the clay. Therefore, under humid conditions the barrier assumption will have a negligible effect, but under arid conditions with occasional wetting the amount of percolation may be underpredicted. The underprediction, however, would be largely compensated over extended simulation periods.

Lateral Flow Submodel

The lateral flow submodel of the HELP program is based on a linearization of the Boussinesq equation:

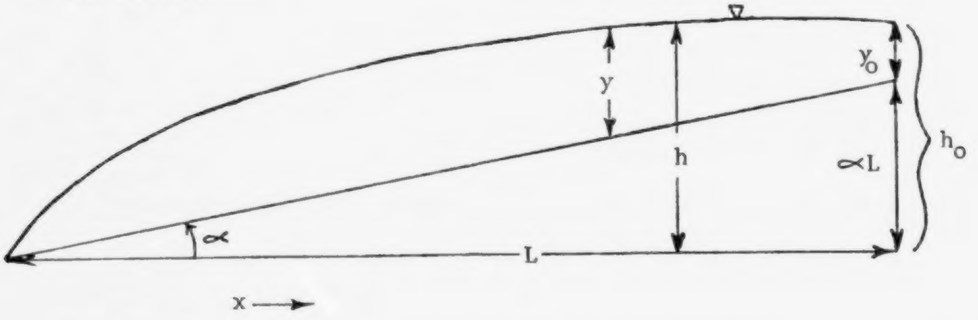

Figure 3. Configuration of lateral flow submodel.

$$f \frac{\partial h}{\partial t} = k \frac{\partial}{\partial x} \quad (h-\alpha x) \frac{\partial h}{\partial x} + R \qquad (20)$$

where f = drainable porosity

h = gravitational head

k = hydraulic conductivity for lateral flow

t = time

x = lateral distance

α = fractional slope

R = recharge flux

The model configuration is illustrated in Figure 3 for a landfill that is 2L wide and has side slope equal to α. For application in the HELP model, a steady-state assumption is used:

$$\frac{\partial h}{\partial t} = 0 \qquad (21)$$

such that no change in head occurs during a computational time step. The steady-state assumption places certain restrictions on the magnitude of computational time steps. This will be discussed further in the section on model testing.

With the steady-state assumption, Equation 20 may be rewritten as:

$$\frac{d}{dx} \left(y \frac{dh}{dx} \right) = - \frac{k}{R} \qquad (22)$$

where $y = h - \alpha x$.

Equation 22 was linearized by Skaggs (10) to the following form by substituting $\bar{y}$ for y and integrating subject to the boundary conditions:

$$h = 0 \text{ at } x = 0 \qquad (22a)$$

$$\frac{dh}{dx} = 0 \text{ at } x = L \qquad (22b)$$

to obtain:

$$Q_L = \frac{2k\bar{y}h_o}{L^2} \qquad (23)$$

where: Q_L = lateral drainage rate,

$\bar{y}$ = average thickness of flow,

L = maximum length to drain

h_o = elevation of water surface at $x = L$

The vertical flow submodel simulates vertical flow for the entire cross-section shown in Figure 3. Therefore, the thickness of the saturated zone computed in the vertical flow submodel corresponds to $\bar{y}$. Using a finite difference model, developed by Skaggs (10) to solve the Boussinesq equation, lateral drainage rates and water profile were generated for nine combinations of α and L with $\bar{y}$ ranging from 0.2 m to 1.0 m to obtain correction factors for the linearized Boussinesq equation.

Equation 23 may be rewritten with the correction factor as follows:

$$Q_L = \frac{2\ C_1\ k\bar{y}\ h_o}{L^2} \qquad (24)$$

where

$$h_o = y_o + \alpha L \qquad (25)$$

and

C_1 = correction factor

$$= 0.510 + 0.00205\, \alpha L \qquad (26)$$

The variables, y_o and h_o, are unknown during the simulation; therefore, a relationship between $\bar{y}$ and y_o was developed of the following form:

$$y_o = C_2\ \bar{y} \qquad (27)$$

where

$$C_2 = \left(\frac{\bar{y}}{\alpha L}\right)^{0.16} \qquad (28)$$

Therefore, the final form of Equation 23 is:

$$Q_L = \frac{2k\bar{y}(0.510 + 0.00205\alpha L)\left(\bar{y}\left(\frac{\bar{y}}{\alpha L}\right)^{0.16} + \alpha L\right)}{L^2} \qquad (29)$$

where the units of $\bar{y}$ and L are in inches and α is dimensionless.

Linkage Between Vertical and Lateral Flow Submodels

The linkage between vertical and lateral flow occurs through a moisture balance computation in the vertical model which is used to estimate the gravitational head. The gravitational head determines the rate of lateral flow and the rate of percolation. Because the moisture balance is a function of drainage from the profile, and drainage from the profile is a function of the resulting moisture balance, an iterative scheme is required to solve both simultaneously.

The computational scheme begins by taking a previous value as the initial estimate of drainage out of the vertical profile. This outflow rate is used in Equation 15 to compute the moisture content of the bottom segment. The earlier assumption of free outflow from each segment (see Equation 12) could result in an excessive buildup of moisture in the bottom segment. Therefore, each segment, beginning at the bottom of the profile, is checked for apparent moisture content in excess of the available pore space of the segment. Any excess moisture in a segment is distributed upward. If excess moisture results at the top of the profile, it is added to the runoff during the time step.

After the segment moisture contents are balanced by distributing excess moisture upward, the effective gravitational head for lateral flow and percolation is computed with the following equation, beginning at the bottom of the profile:

$$TH = \sum_{j=m}^{n} TS(j)\left[\frac{SM(j) - FC(j)}{UL(j) - FC(j)}\right] \qquad (28)$$

where TH = total head,

TS(j) = thickness of segment j,

m = the bottom segment, and

n = the lowest segment that is not saturated.

The hydraulic conductivity, k, for lateral flow in Equation 23 is also a function of the thickness of flow ($\bar{y}$), if the profile is layered. The conductivity is computed as a head-weighted average of the saturated hydraulic conductivity of each segment that contributes to the head. This can be expressed as:

$$k_L = \sum_{j=m}^{n} k_s(j)D(j)/TH \qquad (29)$$

where k_L = the effective lateral hydraulic conductivity,

$k_s(j)$ = the saturated hydraulic conductivity of segment j

and

$$D(j) = \frac{SM(j) - FC(j)}{UL(j) - FC(j)}\,[TS(j)] \qquad (30)$$

The gravitational head (TH) is substituted for $\bar{y}$ and hydraulic conductivity (k_L) is substituted for k in Equation 23 to compute the rate of lateral flow (Q_L), and the rate of percolation through the barrier by Equation 19. The estimates, Q_L and Q_p are summed and compared with the initial estimate of profile drainage. If this estimate is not within a predetermined tolerance of the previous estimate, a new drainage estimate is computed by the method of bisection. The moisture balance and head computations and the computation of Q_L are repeated until successive estimates of Q_L are within 5 percent of each other.

The steady-state assumption used to link the vertical and lateral flow submodels requires that the computational time step be sufficiently short that there is no appreciable change in head. The stringency of this requirement is reduced somewhat because of the midpoint routing procedure. With the midpoint routing procedure, the computational time interval must only be short enough to keep the rate of lateral flow and percolation constant through the time interval. The length of computational time step must be short when $\bar{y}$ (TH) is large and the drainable porosity is low. Figure 4 shows the rate of change of Q_L as a function of $\bar{y}$ and k_s for a soil with drainable porosity equal to 15 percent. When the soil consists of a loam (k_s = 10^{-4} cm/sec), Q_L varies from zero to 9.4×10^{-4} cm day^{-2} as $\bar{y}$ changes from zero to 150 cm. For a sand (k_s = 10^{-2} cm/sec), however, Q_L varied from zero to 9.34 cm day^{-2} over the same range of head. Q_L for a soil that is intermediate between the

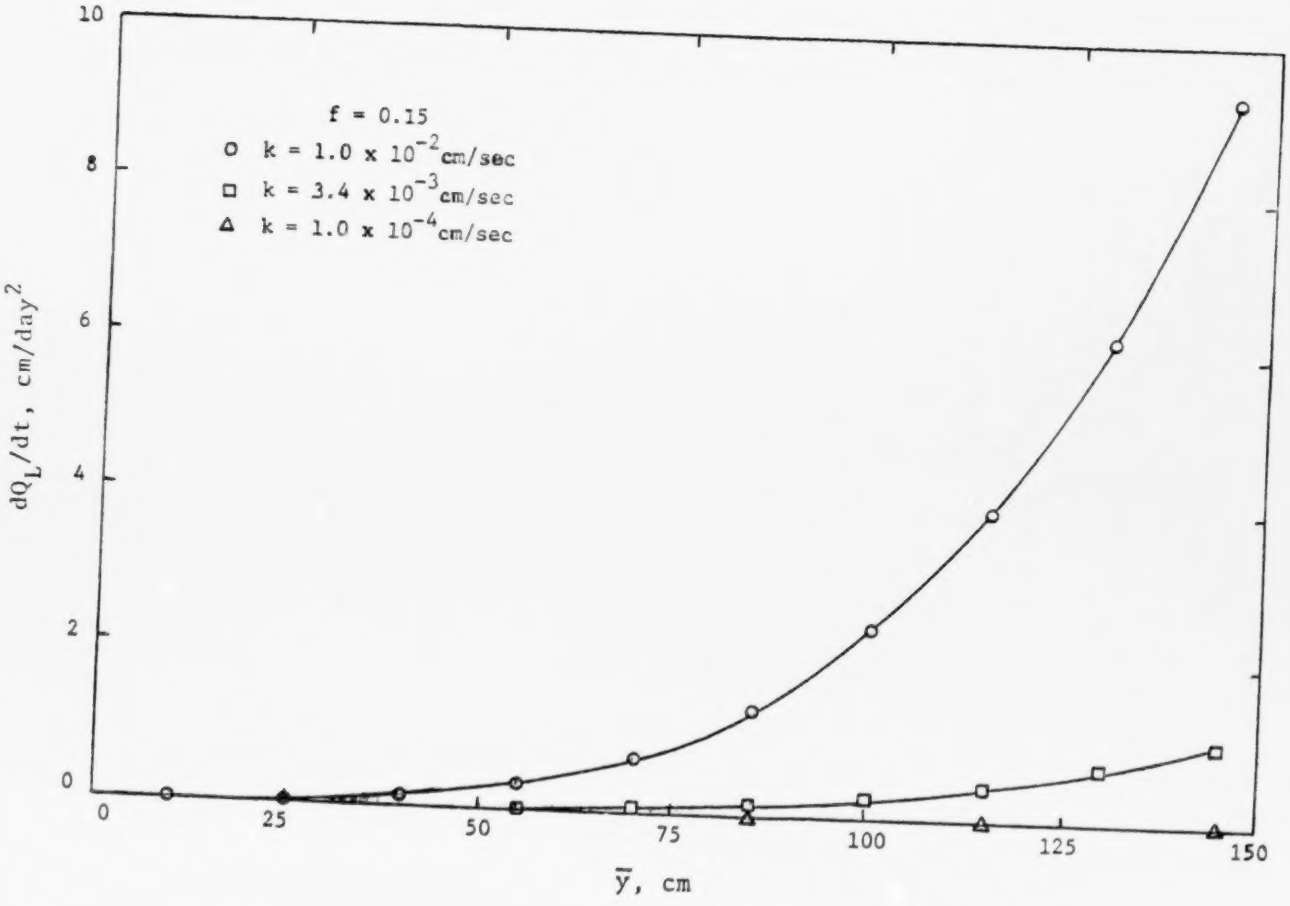

Figure 4. Rate of change in lateral flow rate (Q_L) with head for different hydraulic conductivities (k).

sand and the loam ($k_s = 3.4 \times 10^{-3}$ cm/sec) varies from zero to 1.07 cm day^{-2}. A daily time step would provide sufficient accuracy if the soil has an effective lateral conductivity like that of loam, but a shorter time step is required to simulate lateral flow accurately in a sand when $\bar{y}$ is greater than about 30 cm. A layered soil column consisting of loam over sand, however, would be simulated accurately when $\bar{y}$ is below about 50 cm. If the drainable porosity were reduced, the rate of change of Q_L would be proportionately higher.

To assure acceptable accuracy, simulations were performed varying the computational time step from one day^{-1} to 96 day^{-1}. The accuracy of simulation was found to converge rapidly as the time step was reduced from 1 day^{-1} to 4 day^{-1} and to converge very slowly from 12 day^{-1} to 96 day^{-1}. In an 18-day simulation of drainage from a layered, loam over sand, profile, four time steps per day produced an error that was less than 0.3 cm although $\bar{y}$ was initially at 1 m. It was concluded that four time steps per day (t = 6 hrs.) would give sufficient accuracy for most applications. The error introduced from this decision is expected to be small because the high values of $\bar{y}$, which causes this problem, do not occur with high frequency or last very long.

Use of HELP in Landfill Design

The HELP model, although it is strictly deterministic in structure, is intended for use in evaluating landfill design stochastically. The idea here is that the sequence of precipitation and ET demand is a stochastic process, and so the model output is a stochastic process. Therefore, it is reasonable to test a landfill design with the cover off by simulating twenty years of record then analyzing the frequency of occurrence of certain water table depths, percolation rates, or volumes of leachate to be collected and treated. For this reason it is necessary that the model perform in a realistic manner and that the precipitation-evapotranspiration sequence be representative of the area where the landfill will be constructed.

The HELP model should not be thought of as a predictor of the future. It can be used to compare alternative designs to determine which has the greater probability of acceptable performance. It may also be used to evaluate the probable hazard or probable extent of environmental degradation that has occurred at an existing landfill site. This latter application, however, requires the use of local precipitation and temperature records as well as detailed measurement of soil characteristics and system layout.

Any results generated with HELP, particularly when used to assess the environmental hazard of an existing site, must be taken with the caveat that this model is entirely unverified. It has been developed in a manner that is consistent with accepted soil physical theory, and it has been verified against other equally valid theoretical models, but it has never been tested with field measurement since field verification data are not availalbe. Current work is attempting to generate the data for verification.

Example

This example represents a typical hazardous waste landfill cover (cap) composed of a top layer of soil supporting a fair stand of grass, a drainage layer, and a low-permeability barrier (restrictive) soil liner. No synthetic membrane was used. Default climatologic data describing the precipitation, temperature, solar radiation, leaf area indices, and winter cover factor for New Orleans, LA were used. Default soil characteristics describing the porosities, field capacities, wilting points, hydraulic conductivities, and evaporative (transmissivity) coefficients of the three layers were also used. The input data are presented in Table 1.

The program produces several types of output: optional daily simulation results, optional monthly totals of the water budget components, annual totals, and average monthly and annual totals of the water budget components for the simulation period, and peak daily values of various simulation variables. The nonoptional output for the example is presented in Tables 2, 3, 4, and 5.

SUMMARY

The HELP model is a deterministic, quasi-two-dimensional water budget model developed specifically for the hydrologic evaluation of proposed and existing landfill designs. The model is implemented as an interactive system that can be used

TABLE 1. INPUT DATA FOR EXAMPLE

Parameter	Value
Location	New Orleans, LA
Simulation period	5 years (default data)
Vegetative cover	fair grass (default data)
Evaporative zone depth	20 inches
Area of site	240,000 sq ft
Number of layers	3
Layer 1	
Layer type	1 (vertical percolation)
Soil type	12 (silt/loam, default)
Layer thickness	24 inches
Layer 2	
Layer type	2 (lateral drainage)
Soil type	1 (coarse sand, default)
Layer thickness	12 inches
Drainage length	175 feet
Slope at bottom	3 percent
Layer 3	
Layer type	3 (barrier soil without synthetic membrane)
Soil type	20 (low-permeability clay barrier soil, default)
Layer thickness	24 inches

TABLE 2. ANNUAL TOTALS

Water Budget Component	(Inches)	(Cu. Ft.)	Percent*
1974			
Precipitation	72.79	1,456,000.	100.00
Runoff	10.29	205,800.	14.14
Evapotranspiration	50.26	1,005,000.	69.05
Percolation from base of cover	1.68	33,640.	2.31
Drainage from base of cover	8.98	179,700.	12.34
Soil water at start of year	21.00	420,000.	
Soil water at end of year	22.57	451,400.	
Snow water at start of year	0.0	0.	
Snow water at end of year	0.0	0.	
1975			
Precipitation	80.50	1,610,000.	100.00
Runoff	13.79	275,800.	17.13
Evapotranspiration	52.08	1,042,000.	64.70
Percolation from base of cover	1.79	35,760.	2.22
Drainage from base of cover	13.60	272,000.	16.89
Soil water at start of year	23.57	451,400.	
Soil water at end of year	21.81	436,200.	
Snow water at start of year	0.0	0.	
Snow water at end of year	0.0	0.	

(continued)

TABLE 2. (continued)

Water Budget Component	(Inches)	(Cu. Ft.)	Percent*
1976			
Precipitation	47.36	947,200.	100.00
Runoff	4.21	84,260.	8.90
Evapotranspiration	34.80	696,000.	73.48
Percolation from base of cover	1.37	27,360.	2.89
Drainage from base of cover	5.16	103,100.	10.89
Soil water at start of year	21.81	436,200.	
Soil water at end of year	23.63	472,600.	
Snow water at start of year	0.0	0.	
Snow water at end of year	0.0	0.	
1977			
Precipitation	71.81	1,456,000.	100.00
Runoff	12.64	252,700.	17.35
Evapotranspiration	42.94	858,800.	58.98
Percolation from base of cover	1.90	37,920.	2.60
Drainage from base of cover	16.44	328,900.	22.58
Soil water at start of year	23.63	472,600.	
Soil water at end of year	22.52	450,500.	
Snow water at start of year	0.0	0.	
Snow water at end of year	0.0	0.	
1978			
Precipitation	76.85	1,537,000.	100.00
Runoff	18.24	364,700.	23.73
Evapotranspiration	45.34	906,900.	59.01
Percolation from base of cover	1.89	37,800.	2.46
Drainage from base of cover	14.30	286,000.	18.61
Soil water at start of year	22.52	450,500.	
Soil water at end of year	19.60	391,988.	
Snow water at start of year	0.0	0.	
Snow water at end of year	0.0	0.	

*Percent of annual precipitation.

TABLE 3. AVERAGE MONTHLY TOTALS FOR 1974 THROUGH 1978

Water Budget Component	Jan/Jul	Feb/Aug	Mar/Sep	Apr/Oct	May/Nov	Jun/Dec
Precipitation (inches)	6.54 6.58	3.66 9.84	4.37 5.91	4.55 3.16	7.01 7.12	5.95 5.37
Runoff (inches)	1.62 0.55	0.68 1.93	0.51 1.36	0.84 0.30	1.13 1.45	0.44 1.03
Evapotranspiration (inches)	2.53 5.48	2.58 5.56	4.13 4.32	3.50 2.51	4.93 2.78	4.26 2.53
Percolation from base of cover (inches)	0.15 0.14	0.16 0.14	0.15 0.15	0.14 0.13	0.13 0.13	0.15 0.15
Drainage from base of cover (inches)	1.42 0.86	1.59 0.92	1.16 1.25	0.69 0.76	0.60 0.58	0.66 1.20

TABLE 4. AVERAGE ANNUAL TOTALS FOR 1974 THROUGH 1978

Water Budget Component	(Inches)	(Cu. Ft.)	Percent*
Precipitation	70.06	1,401,000.	100.00
Runoff	11.83	236,700.	16.89
Evapotranspiration	45.09	901,700.	64.35
Percolation from base of cover	1.72	34,500.	2.46
Drainage from base of cover	11.70	233,900.	16.69

*Percent of average annual precipitation.

TABLE 5. PEAK DAILY VALUES FOR 1974 THROUGH 1978

Water Budget Component	(Inches)		(Cu. Ft.)
Precipitation	8.52		170400.
Runoff	4.80		97680.
Percolation from base of cover	0.02		493.
Drainage from base of cover	0.12		2474.
Head on base of cover	35.6		
Snow water	0.00		0.
Maximum veg. soil water (vol/vol)		0.54	
Minimum veg. soil water (vol/vol)		0.24	

without knowledge of computer programming. The interactive system includes default values for all model parameters and representative precipitation and temperature files so that the model can be used in most areas of the United States.

HELP is an extension of the HSSWDS model, which was based on the CREAMS model developed by USDA. Significant refinements have been introduced to the model components for computation of evapotranspiration and water routing. The evapotranspiration component includes a representation of biological control mechanics which limit the rate of evapotranspiration when atmospheric demand is excessive, and a mechanism by which the occurrence of drought (wilting point moisture levels) prevents leaf area index (LAI) from increasing. Whereas previously (in HSSWDS) any moisture which passed through a shallow root zone was assumed to percolate into the waste cell, the HELP model allows a small but significant rate of moisture withdrawal by evapotranspiration to a depth of 120 cm.

The capability of simulating lateral flow above a sloping barrier layer and a rate of percolation through the barrier adds further options to the analysis of landfill designs. The vertical flow model is based on Darcy's Law of flow in porous media, with modification for unsaturated flow. The lateral flow component is based on the Boussinesq equation with a steady-state approximation. The vertical and lateral flow submodels are linked by an iterative procedure that has been optimized to achieve high numerical accuracy while maintaining an efficient longterm simulation.

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GEOTECHNICAL QUALITY ASSURANCE OF CONSTRUCTION OF DISPOSAL FACILITIES

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ABSTRACT

This paper summarizes the technical resource document. The need for a quality assurance program as a management practice which assures the protection of the human health and environment is discussed within the framework of the EPA regulations promulgated on 26 July 1982. The permittee of a hazardous waste disposal facility is shown to be somewhat unique in the construction industry given the three responsibilities: design; construction and operations; and quality assurance; all consolidated with him. The geotechnical parameters which should be tested, observed and documented during the construction, operation and closure of a disposal facility are identified. The limitations of design properties tests and the applicability of index properties tests are discussed. A summarized statistical analysis of sampling size, frequency and distribution to support a hazardous waste disposal facility quality assurance program is presented. Accepted and commonly used methods for testing water content; unit weight; specific gravity; grain-size distribution; liquid limit; plastic limit; cohesive soil consistency; water content/density/compactive effort; cohesionless soil relative density; and geomembranes/geotextiles are identified. The criteria for the selection of a particular test method are discussed. A quality assurance program, suitable for the somewhat unique permittee of a hazardous waste disposal facility, is presented. Considerations for such a quality assurance program are also addressed.

INTRODUCTION

As stated in the Federal Register, 26 July 1982, "EPA wants to make sure that the issuance of a RCRA (Resource Conservation and Recovery Act) permit for a facility means that a certain level of protection is provided and that the public can be assured that the prescribed level of protection will be achieved."

"Section 3004 of RCRA provides that EPA has authority to issue regulations covering owners or operators of (hazardous waste) treatment, storage and disposal facilities as may be necessary to protect human health and the environment." Given this authority the EPA has charted a two "line of defense" protection strategy for hazardous waste disposal facilities. This strategy calls for facility design and operating standards to prevent contamination and a monitoring and response program to detect and correct a condition of contamination should it occur. The EPA believes that adequate protection will be afforded if the technical and environmental performance standards promulgated to execute their two "line of defense" strategy are met. A quality assurance program for the construction, operation and closure of a hazardous waste disposal facility, though not mandated by the current regulations, is a "management practice" which can assure that these standards are met, that the strategy is executed and that human health and the evironment are protected.

Objective of Study

The study is intended to provide technical background for use by designers, specifiers, quality assurance engineers, and permit writers. It addresses the subject of quality assurance of site geotechnical parameters during the construction, operation, and closure of landfills, surface impoundments, waste piles, and land treatment units. It does not address injection wells or seepage facilities.

Scope of the Study

Four major topics are discussed as they relate to the responsibilities of the permittee during construction, operation, and closure of a hazardous waste disposal facility:

(1) Those geotechnical parameters that should be tested and/or observed and documented are identified and described. The reasoning for their selection is given.

(2) Sampling and frequency of testing are discussed. Random sampling plans, sample size selection, and calibration of test equipment are presented using rational, unbiased statistical methods.

(3) The commonly used laboratory and field testing and/or observation methods, needed for investigation of the geotechnical parameters, are identified and described. A discussion of merits and limitations of the various methods is given. Criteria are proposed for selection among alternatives.

(4) A quality assurance program, suited to the unique construction responsibilities of the permittee, is presented and discussed. The documentation necessary to provide a valid record of the quality of the work is recommended.

The Unique Permittee

In most areas of construction there is a contractual relationship between the owner, whether public or private, and the contractor. The owner's designers prepare plans and specifications. The contractor is expected to use those "control of quality" procedures necessary to control his materials and workmanship to comply with the plans and specifications. The owner's inspectors perform those acceptance sampling and testing functions necessary to give confidence to the owner that the materials and workmanship provided are acceptable. This then results in a near adversary relationship between the owner and the contractor.

The permittee of a hazardous waste disposal facility is somewhat unique in the construction industry. Because of EPA policy, the permittee is responsible to the EPA for all three construction related functions:

(1) The Design Function: Including site selection, site characterization, analysis and design, plans and specifications, preparation of the permit application, and verification of design for exposed site media.

(2) The Construction and Operations Function: Provision of all materials and workmanship.

(3) The Inspection Function: All quality assurance activities, including sampling, testing and/or observation, and documentation.

That he is responsible for both construction and inspection poses a potential conflict of interest. The quality assurance program presented later in this paper accounts for the permittee's unique situation and this potential conflict of interest.

GEOTECHNICAL PARAMETERS

In the design of a hazardous waste disposal facility the permittee's design group makes estimates of the engineering properties of the natural site soils and assumptions about the engineering properties of the constructor-placed materials. This requires quantitative and specific information on the physical and strength properties of soils that have direct and valid application to the design problem (ASTM, 1970). These properties include permeability, compressibility, and shear strength. The function of the quality assurance program during construction is to assure the standard of quality specified by the design is achieved. Ideally, quality assurance observations and tests should measure the design properties directly.

Design Properties Tests

The geotechnical tests used to define the engineering properties of soils are:

(1) Permeability

- a. Laboratory permeability tests
- b. Laboratory capillarity tests
- c. Field permeability tests

(2) Compressibility

- a. Laboratory consolidation tests
- b. Swell pressure tests

(3) Shear strength

- a. Laboratory direct shear
- b. Laboratory triaxial compression
- c. Laboratory unconfined compression

Limitations of Design Properties Tests

Although these are the tests that should be made as part of a quality assurance program, they are not normally used because they require (ASTM, 1970; DA, 1970; and Terzaghi, 1967):

- a. Extensive time: The performance of any of these tests can take from one full day to as long as two weeks. Efficient control of construction requires much faster test times.
- b. Complex equipment.
- c. Complex procedures.
- d. Highly trained operators.
- e. Controlled laboratory environment: This implies temperature control and vibration-free surroundings not normally found at a construction site.
- f. High quality undisturbed samples.

Instead, various simpler, faster, index tests, whose results relate to permeability, compressibility and shear strength, are performed.

Criteria for Inspection Tests and Observations

Construction efficiency and control of quality require that nearly continuous tests and observations be made during the progress of the work. Therefore, an inspection test or observation should:

- a. Be a good indicator of a design property. It should correlate well with the appropriate engineering design property by itself or with other, similar tests.
- b. Be accurate and precise. Accuracy can be improved by calibration and should be stable. Precision should be within acceptable, known limits.
- c. Have results quickly available. The test or observation should be capable of being performed in time for an acceptance decision to be made so that minimum interference with contractor performance occurs.
- d. Be easily run using simple, rugged equipment. The test or observation should not require extensive training of the operator or require judgement decisions on his part.
- e. Not require an undisturbed sample, except for density.
- f. Provide test/observation results that are documentable. The test or observation should be a number or a well defined term or phrase.
- g. Preferably be non-destructive. Field tests often require sample removal and replacement or patching.

Index Properties Tests

In the practice of geotechnical engineering, there has been developed a small group of laboratory tests called indicator, or index properties, tests. These are physical tests that have proven to be suitable for quality assurance programs, and some of which have been used in such and similar applications for over 50 years.

The index properties tests useful in a quality assurance program may be placed into three categories:

(1) Weight-volume relationships.

- a. Water content test
- b. Density test
- c. Specific gravity test
- d. Calculated values -- void ratio, porosity, and degree of saturation

(2) Soil classification tests.

- a. Grain size distribution tests
- b. Atterberg limits tests
- c. Consistency tests -- using simple field methods
- d. Calculated values -- plasticity index, liquidity index, activity, and USCS Classification

(3) Laboratory compaction.

- a. Density/water content/compactive effort tests; for cohesive soils and "dirty" granular soils
- b. Maximum and minimum density tests; for clean granular soils

All of the index properties result from standardized soils tests.

Construction Processes

The main tests/observations that should be made for the various construction processes are described below. The emphasis is on a quality assurance program that focuses on catching mistakes before or as they occur, correcting them, testing for specification compliance, and documenting the entire process to provide the necessary confidence in the inspection procedure. This requires continuous, cooperative interaction between the design group, the construction group, and the inspection group. The tests and/or observations that should be made and documented are:

(1) Site preparation.

- a. Observation of the newly exposed ground surface to confirm site characterization
- b. Observation of surface drainage contouring
- c. Observation of behavior of the drainage system

(2) Excavation.

- a. Observation of exposed walls and floor for site media verification
- b. Observe construction surveys for exact trench locations and slopes
- c. Observation of excavation related soil movements, using surveying methods
- d. Observation of placement of erosion control measures

(3) Foundation preparation.

- a. Observation of stripping
- b. Observation of soil and rock surfaces
- c. Observation of construction of underseepage cutoffs

(4) Compacted earth fill.

- a. Quality of the borrow soils
- b. Atmospheric conditions recorded
- c. Equipment suitability
- d. Lift thickness
- e. Compactive effort (number of passes) and uniformity of rolling
- f. Compacted density and water content

(5) Liner materials and geotextiles.

- a. Identification of materials used

b. For admixed materials, the application rate, blending, spreading, rolling, layer thickness, and density (see Compacted earth fill above)

c. For geomembranes and geotextiles, the identification of material, smoothness of placement surface, method of placement, and imperfections

d. For geomembranes and geotextiles, the seam overlap, seam sealing, and seam integrity tests

(6) Hydraulic collector.

a. Observation of the surface of the impermeable base for imperfections

b. Observation of the amount and direction of slope

c. Quality of permeable materials

d. Tests of placement of granular materials

SAMPLING TECHNIQUES

The method and frequency of sampling and testing in construction had traditionally been based on intuitive decisions of the sampler or his superiors. The purpose of sampling and testing is to provide data for evaluation of a portion of the work. Unless sampled by probability, or random, sampling methods, the result is often a biased and nonrepresentative estimate of a quality characteristic. Frequency of sampling and testing can only be rationally discussed in statistical analysis terms. It is a function of desired level of confidence, maximum error or percent error, and the actual variability of the tested quality characteristic in the sampled portion of work. Comparison of standard and alternative test methods can be made on the basis of sample sizes needed for equivalence of confidence levels.

Frequency of Sampling and Testing

There is an inherent variability in measurement data for any specified quality characteristic of any soil mass, whether natural or construction-processed. Variability in measurements occurs as a result of (a) material composition variability, (b) placement (formation) process variability, and (c) measurement process variability. All measurements contain variability from all three causes combined.

Each individual measurement of a quality characteristic may be considered to be one of a "countably infinite" number of similar measurements that could be made in a universe of the material. The difference or error between the measured value and the "true" or reference value is the sum of components, an accuracy (systematic or calibration) error and a precision (random) error. This can be written as (ASTM, 1982):

$$X = \mu_R + \delta + \varepsilon \qquad (1)$$

and

$$\delta = \mu_R - \mu_P \qquad (2)$$

where

X = numerical value of a measurement

μ_R = true or accepted reference level of the property of the material to be measured

μ_P = expected value or the average of many observations recorded for the process

δ = correction for consistent or systematic error of the measurement process at the reference level μ_R

ε = correction for random deviation about the average of the observations μ_P

Accuracy refers to the degree of agreement of individual measurements or the average of a large number of measurements with a "true" or accepted reference value. This implies the idea of a consistent deviation, or systematic or bias error, which is fixed or common contribution to error in each of a sample of measurements. Precision is the degree of mutual agreement among individual measurements of a consistent material made under prescribed, like conditions. The imprecision of measurement may be characterized by the standard deviation of the errors of measurement.

In Equation 1, the δ-term for correction for systematic, or accuracy, error is the sum of corrections from each of the three causes of nonrandom variation. This is then written:

$$\delta = \delta_M + \delta_P + \delta_T \tag{3}$$

where

δ_M = correction for systematic error due to material composition

δ_P = correction for systematic error due to placement process

δ_T = correction for systematic error due to testing process

Because the effects of material composition, placement process, and testing process are interrelated, it is not usually possible to differentiate these in a group of measurements. If the material composition and placement process effects are combined into a material quality effect, then:

$$\delta_Q = \delta_M + \delta_P \tag{4}$$

and

$$\delta = \delta_Q + \delta_T \tag{5}$$

where

δ_Q = correction for systematic error of the measurement process at the reference level μ_R due to the material quality, the combined effects of material composition and placement process

The precision term of Equation 1, ε, is a random effect, and is the combination of random effects due to the three causes discussed above. The statistical variace, σ_0^2, of a group of measurements of a characteristic of a consistent material using a consistent test method is the sum of the variance due to the three causes of random variability. This may be given as:

$$\sigma_0^2 = \sigma_M^2 + \sigma_P^2 + \sigma_T^2 \tag{6}$$

and defining

$$\sigma_Q^2 = \sigma_M^2 + \sigma_P^2 \tag{7}$$

then

$$\sigma_0^2 = \sigma_Q^2 + \sigma_T^2 \tag{8}$$

where

σ_0^2 = overall variance

σ_M^2 = variance due to material composition

σ_P^2 = variance due to placement process

σ_T^2 = variance due to testing process

σ_Q^2 = variance due to material quality

If the variance due to a particular testing process, σ_T^2, is known, or can be estimated, then its effect on the overall variance, σ_0^2, can be evaluated from Equation 8 as:

$$\sigma_0 = \sigma_Q \sqrt{1 + \left(\frac{\sigma_T}{\sigma_Q}\right)^2} \tag{9}$$

where

σ_0 = total standard deviation

σ_Q = quality standard deviation

σ_T = testing standard deviation

When comparing alternative test methods, the effect of different standard deviations of the test methods on the overall standard deviation should be considered. It can be seen from Equation 9 that when material quality is uniform (low σ_Q) the precision of the test method (σ_T) is of great importance. However, when material quality is not uniform (high σ_Q) the relative precision of one test method (σ_T) versus another is of little overall importance.

Types of Sampling

Probably the most satisfying method

to the engineer concerned about sampling all parts of the block is a combination of (a) stratified random sampling and (b) systematic sampling with a random start.

If a universe, or block, consists of, or can be divided into, a group of strata, then a random sample can be drawn from each stratum instead of drawing a single random sample from the entire population. This is called *stratified random sampling*. The division of a soil mass or a construction process into blocks is a form of stratified random sampling.

A popular sampling method is *systematic sampling with a random start*. This method involves the selection of successive sample units at uniform intervals of time, distance, area, or volume. It is argued that if the first sample unit is selected at a random location, then all successive units are random also.

By subdividing each block of work into a convenient large number of subblocks, using a random start, and following a systematic pattern, a random sample with uniform coverage of the block is obtained.

Selection of Sample Size

A statistically rational and valid method of selecting sample size is given in ASTM (1982) Designation E 122-72, Standard Recommended Practice for Choice of Sample Size to Estimate the Average Quality of a Lot or Process. The equation for the number of units (sample size, n) to include in a sample in order to estimate, with a prescribed precision, the average of some characteristic of a lot is:

$$n = (t\sigma'/E)^2 \qquad (10)$$

or, in terms of coefficient of variation

$$n = (tV'/e)^2 \qquad (11)$$

where

n = number of units in the sample

t = a probability factor, from the Tables of Students'-t

σ' = the known or estimated true value of the universe, or lot, standard deviation

E = the maximum allowable error between the estimate to be made from the sample and the result of measuring (by the same methods) all the units in the lot

V' = coefficient of variation $= \sigma'/\bar{X}$, the known or estimated true value of the universe or lot

e = $E/\bar{X}$, the allowable sampling error expressed as a percent (or fraction) of $\bar{X}'$

$\bar{X}$ = the expected (mean) value of the characteristic being measured

TESTING

Previously in this paper the geotechnical parameters, that should be observed or tested during the construction of a disposal facility, were identified. (For the purpose of this paper, an *observation* usually does not involve a formal or specific method, whereas a *test* almost always involves a specific technique and often a specific piece of equipment.) Standard laboratory or field test methods exist for each of the soil index properties that were identified and defined.

This section of the paper identifies the standard test methods for the soil index properties. For most of these, there exist commonly used alternative test methods; these are also identified.

The following discussion includes only those tests that were identified earlier in the paper. They are the ones considered most appropriate for both process control and acceptance inspection during construction. Although not discussed here, other tests may be used for special investigations during construction, but usually not on a routine basis. These include such tests as the engineering properties tests (mentioned earlier), geochemical tests, hydrology-related tests, off-site evaluations of off-site materials, and material-specific tests of nonsoil materials such as portland cement, asphalt, bentonite, and others.

Criteria for Test Method Selection

With the exception of the nuclear gage moisture/density test, the density part of volumetric field density tests, the air lance test, the vacuum seam test and the conductivity test, all of the standard test methods require (a) procurement of a sample from the field and (b) performance of a test in a laboratory environment. This usually involves the availability of electric power, a water supply, freedom from dust and vibration, and controlled temperature humidity. These are conditions found in a central testing laboratory, and are available only in a few well-equipped construction site laboratories, usually found only on large construction projects. In response to this, and for the other reasons given below, alternatives to the standard test methods have come into common use for construction quality control. The criteria for selection among alternatives include:

a. Time; speed of testing and/or speed of obtaining test results. The efficient use of men and machinery on a construction site demands that the results of quality control testing be available quickly. Construction costs can be one or more hundred dollars per hour. The cost of rapid testing must be compared to the total cost to the permittee due to a slower test method.

b. Correlation with the standard test method. A reasonable reproducibility of test results must be obtainable if test operator or specific test equipment is changed. Accuracy must be stable so that a calibration correction can be made; precision must be such that a reasonable number of tests can be averaged to yield the required confidence.

c. Adaptability to field laboratory conditions. The absence of electric power, the absence of water, and/or the absence of environmental controls can effectively eliminate certain standard test techniques.

d. Adaptability to on-site use. For example, soil density is more readily measured in place rather than by use of an undisturbed sampling method with laboratory measurement of density.

e. Equipment cost; comparison can be made in terms of capital cost of test equipment, relative operator cost, cost of field laboratory services, and need for rapid test method. Expensive, automated equipment cannot be justified if less costly apparatus will provide equivalent results in sufficient time for effective action, especially during small, slow-moving construction processes.

f. Simplicity and ruggedness of equipment; acceptable precision and sensitivity of equipment can often be achieved with apparatus that is simpler to use and more durable under field conditions than more sophisticated devices. The level of necessary operator training, and operator fatigue and/or boredom, can seriously affect repeatability of a test method.

g. Nondestructive testing; this is of particular importance where the act of sampling causes a discontinuity that must be repaired. For example, securing a test coupon from a geomembrane seam requires placement of a secure patch to maintain impermeability.

Soil Index Properties Test Methods

The listing given below includes the standard laboratory test method for each of the index properties. In most instances, alternative standard or nonstandard methods are in common use. There are undoubtedly other alternative methods for some of the tests that are used by various testing groups for construction

(1) Water content test

- a. Standard oven-dry method.
- b. Standard nuclear moisture/density gage method.
- c. Gas burner (frying pan) method.
- d. Alcohol burning method.
- e. Calcium carbide (speedy) method.
- f. Infrared oven or hot air method.

(2) Unit weight test

- a. Standard laboratory volumetric method.
- b. Standard laboratory displacement method.
- c. Standard field sand cone method.
- d. Standard field water balloon method.
- e. Standard field drive cup method.
- f. Standard nuclear moisture/density gage method.

(3) Specific gravity test

Standard laboratory method.

(4) Grain-size distribution test

- a. Standard sieve analysis (+200 fraction) method.
- b. Amount of soil finer than No. 200 screen (wash) standard method.
- c. Standard laboratory hydrometer (-200 fraction) method.
- d. Pipette method for silt and clay fraction.
- e. Decantation method for silt and clay fraction.

- b. Standard one-point me

(6) Plastic limit test

Standard laboratory method.

(7) Cohesive soil consistency test

- a. Standard unconfined compressio test method.
- b. Field expedient unconfined compression test method.
- c. Hand (pocket) penetrometer method
- d. Hand-held Torvane method.

(8) Water content/density/compactive effort tests

- a. 25-blow standard Proctor compaction method.
- b. 25-blow modified Proctor compaction method.
- c. Nonstandardized Proctor compaction methods.
- d. Rapid, one-point Proctor compaction method.
- e. Rapid, two-point Proctor compaction method.
- f. Hilf's rapid method.
- g. Ohio Highway Department nest of curves method.
- h. Harvard miniature method.

(9) Cohesionless soil relative density test

- a. Standard laboratory maximum density method.
- b. Standard laboratory minimum density method.
- c. Modified Providence method.

(10) Geomembrane/Geotextile test

a. Bonded seam strength method.

b. Breaking strength method.

c. Peel adhesion method.

d. Air lance method.

e. Vacuum seam method.

f. Conductivity method.

Observation Techniques

Observations are not dependent on the specifics of a particular technique. Most involve visual evaluations, or simple counting and tabulation, or are simple length or thickness measurements. The usual procedures for these observations are either straightforward, requiring no special instruction or equipment, or they involve visual comparisons that are either site-specific or material-specific. Specification writers and permit writers should simply state the desired end result and leave the determination of technique to the experience and ingenuity of the inspector or his superior.

As an example of the statements made above, the smoothness and freedom from sharp objects of the soil surface to receive a geomembrane can only be accomplished by 100 percent visual inspection. This is also true in the observation for freedom of the placed membrane from tears. The thickness of a soil lift prior to compaction can be quickly and easily checked with a marked rod, or even a suitably marked spade. The observation of a freshly cut trench wall or floor starts with visual inspection for texture and color patterns, supplemented by field expedient soils tests using the visual-manual procedure. Sampling and testing plans for site media verification studies can then be effectively made. The results of the observation depend more on the technical expertise and willingness of the inspector than on specific details of technique.

THE QUALITY ASSURANCE PROGRAM

As stated earlier in this report the permittee of a hazardous waste disposal facility is somewhat unique in the construction industry. Because of his unique situation the permittee is confronted with a potential conflict of interest between his construction and operations responsibility and his quality assurance responsibility.

Those factors that make his situation unique, and that affect the quality assurance program, are:

(1) The permittee has total responsibility for design, construction, and inspection within his own organization.

(2) The permittee must give confidence, or assurance, to the EPA in the quality of his work.

(3) The permittee passes judgement on his own work.

(4) A disposal facility can be a relatively small project with only a few workmen and pieces of equipment operating at any time.

(5) The permittee's organization is relatively informal, with sometimes blurred lines of authority and responsibility.

Considerations for a Quality Assurance Program

The permittee should consider all of the following before establishing a quality assurance plan: quality personnel management; attitude of the workmen, construction management, and inspectors toward quality; the nature and cost of a quality assurance program; the human factor; and the problem of scale.

Quality Personnel Management within the Permittee's Organization. The permittee can be assured that his desired standard of quality is achieved by the implementation of an effective quality assurance program within his organization. Such a program would undoubtedly include management practices with the objective of effecting worker performance.

For the purpose of this paper, the implementation of management practices to effect worker performance, such as those recommended by Harris and Chaney

(1969), shall be called quality personnel management. Quality personnel management includes but is not limited to practices such as proper supervision, personnel selection, inspection techniques, and quality assurance jobs definitions. It also includes measures to enhance worker education, participation and satisfaction. It includes other positive motivators such as measures to enhance worker identification with the work, including having workers sign their work. It also includes negative motivators which "push" towards the desired standard, e.g. the threat of a reprimand, as opposed to positive motivators which "pull." In summary quality personnel management includes all the management practices which effect worker performance to give a measure of assurance that the desired standard of quality is achieved.

Quality personnel management within the permittee's organization is a responsibility of the permittee. Also quality personnel management within the permittee's organization is, in general, of no more peculiar significance in the construction of a hazardous waste disposal facility than it would be in any other construction endeavor undertaken by the permittee's organization.

Workman/Management/Inspector Attitude Towards Quality. The individual workman is the ultimate determinant of quality. There is a continual conflict between his desire to achieve high productivity and to do the work "right" as he knows it. He, and his supervisors, may feel that the project is overdesigned at times. They may then develop a "rebel" attitude, in which they will show the inspector that they have as much knowledge as the designers.

The inspector can be part of a team or can be the adversary of construction. He may develop a bias towards or against the construction group. The inspector must be qualified for his work and must not be given the job as a reward for long service.

The Nature of a Quality Assurance Program. The nature of a quality assurance program should match the nature of the design. That is, the design for a relatively high standard of quality (e.g. for a site where the complex geology and the protection of the human health and environment require that extensive measures be undertaken) calls for a program which gives a great deal of assurance that the high standard of quality is achieved. Conversely, the design for a lesser standard of quality (e.g. for a site with an ideal geology and climatic conditions, and where little threat is posed to the protection of the human health and environment) does not call for that same program which gives that great deal of assurance that this lesser standard of quality is achieved. Simply stated, a design for a relatively high standard of quality calls for a program which gives a high assurance that the standard is achieved. And a design for a relatively low standard of quality calls for a program which gives a lesser, but sufficient, assurance that the standard is achieved.

The Human Factor. There can never be absolute certainty that the desired quality is everywhere achieved in the construction of a hazardous waste disposal facility. There exist too many variables, particularly given the inevitable gaps in our knowledge of the soil conditions. However, a quality assurance program does give a measure of assurance, of confidence, that the standard of quality desired and designed for is achieved. The better the quality assurance program the greater this measure of confidence can be. And given the EPA's two-pronged, prevention and cure, protection strategy, the inevitable uncertainty of the quality has been accounted for by the regulatory provision of the monitoring and remedial action procedures.

One significant variable that can be addressed and limited by a quality assurance program is the human factor. Harris and Chaney treat this entire subject in their text, Human Factor in Quality Assurance. Their text is recommended to the reader interested in all aspects of the human factor in quality assurance. The remainder of this section will focus on the human factor variable as it is of peculiar significance in the consideration of a quality assurance program for the construction of a hazardous waste disposal facility.

Through its permit issuing agency, EPA can be assured that the desired standard of quality is designed for by the permittee. But what assurance is there that the standard of quality contained in the design is achieved in the construction and operation of the facility?

The permittee suffers from an inherent conflict of interest in the fulfillment of his construction and operations responsibilities vis-a-vis the fulfillment of his quality assurance responsibilities. Possible manifestations of this conflict of interest are obvious. What does the permittee do when told by his quality inspector that an entire block of work is rejected and must be done again because it is just barely below the standard of quality in the design? What does the permittee do when motivated by the opportunity to maximize profits and believing to himself that government approved designs always include an excessive margin of safety?

This conflict of interest, this human factor, must be addressed in an effective quality assurance program.

The Problem of Scale. As stated earlier, the permittee of a hazardous waste disposal facility is somewhat unique. Although there are other organizations in the construction industry which also have all these responsibilities (design, construction and operations, and quality assurance) and thus are similar in concept, there exist significant differences between these organizations because of the problem of scale. An example of such a seemingly similar organization is that of an organization constructing a nuclear power facility.

In the construction of a nuclear power facility a large organization, what might be considered an institution, has the three responsibilities. In order to protect the reputation of the organization, the present and future jobs of its employees, the huge financial stake in the project, and the professional status of its engineers, this institution has many positive motivators to achieve the standard of quality contained in the design. In order to avoid the adverse consequences of all possible future litigation, the institution also has a strong negative motivator to achieve the standard of quality contained in the design.

In the construction of a hazardous waste disposal facility, it is entirely possible for a very small organization to have all three responsibilities. Hypothetically, that small organization could be dominated by one individual. Thus, this hypothetical organization would act less like an institution and more in a manner reflective of the dominant individual's personality. Thus this organization might be willing to cut corners and take risks. The standard of quality achieved by the organization would then be that set by the dominant individual and not that contained in the design.

So although the two organizations described above are similar in concept, in that both have all three responsibilities, there exists the real likelihood that they might differ in action because of their dissimilarity in size: the problem of scale.

The Quality Assurance Plan

It is recommended that the permittee develop a formal, written plan of action for implementing a QA program. This should include such items as: an organization plan; details of QA methods; names and qualifications of individuals for QA; the procedures for review of data; procedures for reporting; and procedures for assigning responsibility.

Quality Assurance Documentation

Considering all of the factors discussed above, it is recommended that the following documentation of tests and observations be made:

(1) Daily inspection reports

(2) Data sheets for all tests and observations

(3) Block evaluation reports, showing all data and statistical analyses

(4) Design acceptance reports, presenting a review of the block reports and their comparison with design requirements

(5) A summary and checklist for each major section of the project made after its completion

The documentation program given above is intended to provide (a) motivation for an effective QA program, (b) data in the event remedial action is required in the future, and (c) factual information in the event of litigation.

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SECONDARY EMISSIONS FROM HAZARDOUS WASTE DISPOSAL LAGOONS: FIELD MEASUREMENTS

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ABSTRACT

Field measurements of the emission of methylene chloride and toluene from surface impoundments at a site intended for hazardous waste disposal were made by the concentration profile technique. The technique employs profiles of chemical concentrations, temperature and wind speed to quantify chemical emission rates. One significant feature of the method is that it does not disturb the natural transport processes in effect on the water surface. The method is limited with respect to sample time, wind speed, fetch-to-height ratio of upwind disturbances, etc. Observations of chemical concentration in air, wind speed, and temperature are made at six heights within the turbulent boundary layer above the surface. The chemical concentration and velocity vs ln-height profiles should be linear over the full range of six observation heights only if the air boundary layer is neutral. The profiles will likely be non-linear under stable and unstable micrometeorological conditions and thus display some curvature. Various equations may be used to determine flux values of the chemicals depending on the conditions. Flux values deduced from these measurements were compared to those calculated by the Cohen, Cocchio and Mackay model and were found to be in general agreement, although a number of inconsistencies were observed.

INTRODUCTION

It is probable that volatile chemicals can be and are emitted from various types of waste impoundments, and in particular, from surface impoundments such as oxidation lagoons, holding basins, evaporation ponds, etc. Such emissions constitute possible sources of undesirable air pollution and have been the subject of a number of laboratory studies and reviews (1-4) which have proposed models and simulated waste sites in wind tunnels in an effort to quantify the processes.

Thus far, however, it has been difficult to establish the validity of the models and/or predictive equations by comparison with field measurements of emissions from actual impoundments.

Not the least of the difficulties has been the frequent reluctance of the operators to allow the required access to the waste impoundments. However, there are also technical problems in the field measurements as well, and in particular, some methods will interfere with the process of volatilization under study as for example, floating a container or vessel on the water surface, so as to confine and/or capture the escaping vapors will seriously interfere with the process being studies. Other methods, such as sampling upwind and downwind, then estimating the area emission based on dispersion models requires the estimation of atmospheric parameters as well as evaluation of the surrounding terrain and its effect on the dispersion. There are inadequate methods of accounting for other than ideal flat terrain, and methods based on dispersion also require relatively small changes in wind velocity and direction over an extended time.

One method of field measurement develed by Thibodeaux (5), called the "concentration-profile" (CP) method eliminates some of the difficulties in that it doesn't disturb the process and relies on simultaneously measureable atmospheric parameters. This method was used in the present work and will be briefly described.

The CP method involves measurement of the concentration gradient of a chemical of interest above the surface. Then, combined with simultaneously measured air stability parameters (velocity and temperature gradients), the average flux (mass rate of flow per unit area) can be determined for the immediate upwind surface. If the upwind flux were variable with the fetch, then this is an averaging method.

The method was employed in the present instance by drawing samples of air through six different adsorbent tubes simultaneously from six different elevations off the water surface. Hwang (8) has recently proposed a modification of the CP technique which reduces the number of air samples from six to one. This alternative has not yet been adopted.

The CP method must be used in the presence of a wind, prefereably between two (2) and six (6) m/s at a height of one to two meters above the surface. Theoretically the method would be immune to the presence of a uniform background concentration of chemical since it depends only on the concentration gradient with height off the surface. In practice, however, a background presence would be undesireable, not only from a measurement standpoint, but also would preclude testing a model for emissions which assumes no such background concentration. Additional details on the use of the method are presented later. It has also been described in detail elsewhere (6,7).

The CP method was used to determine the emission flux for two chemicals (methylene chloride and toluene) from three evaporation ponds located at a waste treatment facility in Western United States.

Nature of the Site

The three equally sized ponds were located adjacent to each other as shown in Figure 1. The berm heights were variable, but ranged from approximately three feet to approximately twelve feet.

These ponds constitute what the facility operators call "evaporation ponds." They regularly receive aqueous waste containing organic materials and water loss then occurs by evaporation. Some biological decomposition is anticipated as evidenced by the presence of the surface aerators on ponds No. 1 and No. 3.

The circled numbers in Figure 1 show the approximate location of the sampling apparatus for the samples (profiles) indicated. In each case, the location was selected so as to be downwind of the maximum expanse of pond surface with the existing wind.

The volatile priority pollutants in each of the ponds are listed in Table 1 (10). It should be noted that other volatile species were also present, but are not indicated in Table 1.

One of the ponds, No. 1 as indicated in Figure 1, was partially covered with an oil slick, approximately as outlined in Figure 1. The oil slick was moved about considerably by the wind and tended to collect on the downwind side of the pond. During sampling on pond No. 1, the slick covered only about ten (10) percent of the lagoon beyond the oil booms. Since the booms held a much heavier layer of oil behind them, the wind did not expose much water behind the oil booms.

During sampling, neither of the aerators were in operation. The weather was mostly sunny and warm, with winds ranging from near calm to around (5.4 m/s) at a few feet off the surface. Sampling was done only during the daylight of two days.

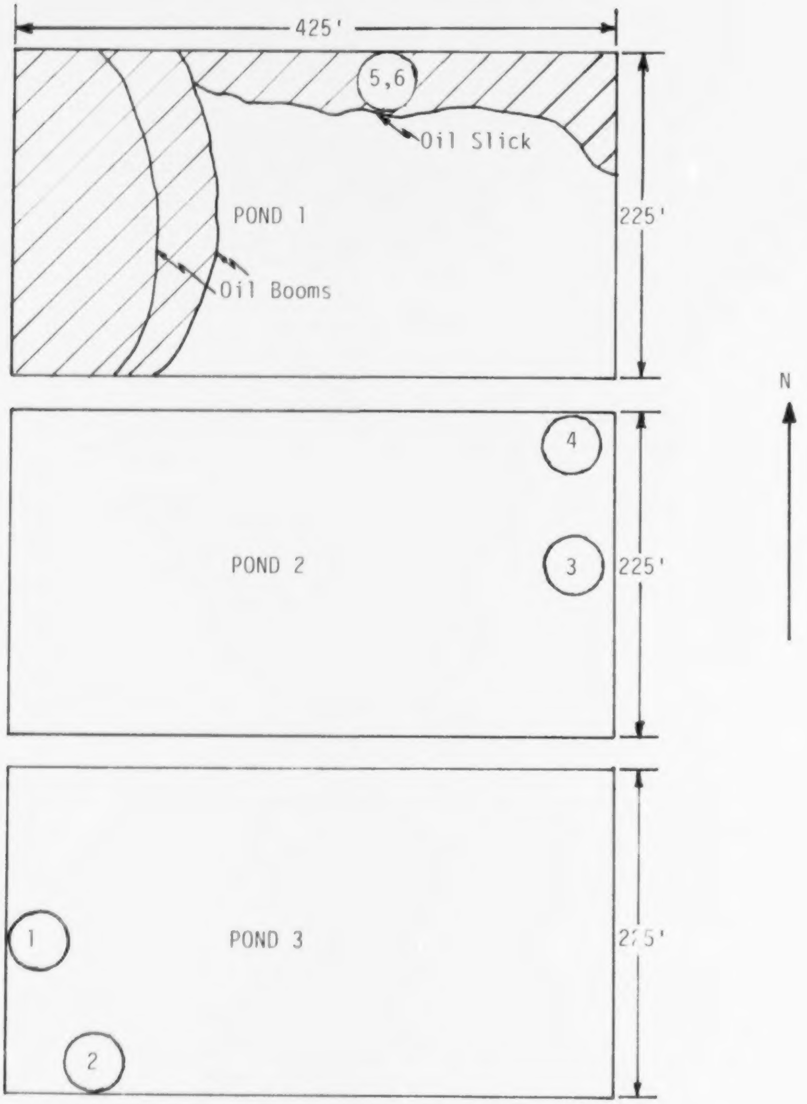
425'
5,6
Oil Slick
POND 1
225'
Oil Booms
N
4
POND 2
3
225'
1
POND 3
225'
2

FIGURE 1 - PLAT AND SAMPLE LOCATIONS
Circled numbers are sample locations

Table 1 - Water Analysis Results

Concentrations in ug/l

Component	Pond 3 (Profiles 1 & 2	Pond 2 (Profiles 3 & 4	Pond 1 (Profiles 5 & 6
Methylene Chloride	10	440	330
Toluene	28	350	51
1,1,1-Trichloroethane	57	45	670
Benzene	...	14	...
Ethylbenzene	...	13	...
Chloroform	...	...	21
Tetrachloroethylene	...	...	18

SELECTION OF SAMPLING

Description of the Sampling Apparatus

Samples of volatile chemicals in the air were collected and concentrated on an adsorbent (Tenax). The apparatus consisted of various devices installed onto a boat for the simultaneous measurement of dry-bulb temperature and wind speed and obtaining air constituent samples. Placement of the apparatus on a boat allowed optimal location on the impoundment surface.

The sample collection devices (sample concentration tubes) were short sections of tubing packed with an adsorbent polymer (Tenax, GC 60/80 mesh). These tubes were 15cm (5.98 inches) in length, 0.125 inch (3.2mm) O.D. and 0.085 inch (2.2mm) I.D. Each tube was packed with approximately 11cm of the Tenax and approximately 2.5cm of silica gel. The tubes were preconditioned by heating to 270°-300°C while purging with helium for not less than one hour. The tubes were fitted with Swagelok caps on each end, and were sealed before and after sampling. Air was drawn through the Tenax end using a vaccuum supplied by a hand-pumped tank.

Water sample containers were small-mouth, amber glass, 1 liter bottles with Teflon lined caps.

Wind speed was measured with a wind profile register system, Model 106 as manufactured by the C. W. Thornthwaite Associates. This device has six cup anemometers spaced one above the other at heights of 20, 40, 80, 120, 240 and 320cm.

The sampling and temperature measurement mast was designed and constructed at the University of Arkansas. The tubing leading from the sampling location to the sample concentration tubes (previously described) was 0.25 inch (6.4mm) O.D. by 0.21 inch (5.3mm) I.D. These tubes terminated at a Swagelok reducing union to which a sample concentration tube could be attached. The outer ends of the lead in tubes were fitted with Swagelok caps so that they could be sealed and maintained in a clean condition during transport and storage.

At the outer end, or air entry location, a temperature sensor was attached to each of the sampling tubes. The sensors were Chromel-Alumel thermocouples in each case which terminated at a multiposition selector switch. The thermocouple junctions were centered inside 2-1/2 inch long pieces of white polyvinly chloride pipe, 3/4" nominal size, which provided radiation shields for the junctions. From the selector switch, a single pair of Chromel-Alumel extension wires was connected to an Omega Engineering Co., Model 410A digital readout meter.

The complete sample collection mast could be moved up or down without changing the relative position of the sampling and temperature measurement points. The sampling elevations were such that if the bottom inlet were 5cm above the water surface, the sampling elevations would be approximately 5, 11, 25, 45, 90, and 180cm above the surface. The elevations were chosen to fit the logarithmic scale used in calculations.

Downstream of each sample concentration tube, the air passed through a rotometer (Matheson Model 7400) and from the rotometer to a common vacuum manifold. A vacuum was used to draw the ambient air through the sampling tubes in order to control flow rates. The samples must be taken over a long enough time period to accommodate varying wind speeds. Thus, the flow rate over this time period was regulated to obtain a predetermined volume of air passing through the sampling tubes. The vacuum was provided by a hand-pumped tank of about 70 liter volume. The flow through all the samplers could be started and stopped simultaneously and each could be individually adjusted by a needle valve on the rotometer, to maintain a steady, equal flow rate in each tube.

The equipment described in the foregoing was mounted on the deck of a boat, which in turn, was moored to the shore to provide stability.

Description of the Sampling Procedure

The apparatus, as described was assembled on a small boat moored to the shore so as to provide the maximum fetch with the available wind. Air samples were drawn through the sample concentration tubes, with the air entering the end containing the Tenax. The air flow rate was adjusted so as to pass one liter of air through each sampler in thirty minutes, to obtain the sample over a reasonable period of time.

Simultaneously with the start of sampling, the anemometer counters were started. Similarly, they were stopped simultaneously with the stopping of the sampling.

At one or more times during the thirty minute sampling times, the temperatures were read at each of the six elevations. Also during the thirty minute period, two water samples were collected at a location close to the sampling location. The water sample was immediately acidified with concentrated hydrochloric acid prior to capping in order to minimize biological activity. The water samples were refrigerated upon return from the field until they were shipped to the contractor's laboratory for analysis.

At the finish of a sampling, the sample concentration tubes were tightly capped and held for later analysis.

Analytical Equipment and Procedures

The analysis of the water samples as reported in Table 1 were performed by a contractor (Mead Compuchem; Durham, N.C.) using a gas chromatograph/mass spectrophotometer. Quality assurance measures were adopted for the analytical techniques. Based on the information supplied by the facility operators, some knowledge was available on the identity of the volatile chemicals present. In the laboratory, external standards were prepared using the sample tubes with Tenax and silica gel spiked with selected volatile chemicals and optimal desorption operating conditions and recovery efficiencies were obtained. These standards were prepared by purging water solutions and adsorbing in the tubes. This was done prior to analyzing any of the field sample tubes.

The method employed to analyze the air samples was essentially as follows: The Tenax traps were thermally desorbed at 180°C for 12 minutes in an aluminum block heater with the helium carrier gas flow (40 ml/min). The effluent from the traps was collected in a cryogenic, capillary trap cooled with liquid nitrogen.

The samples were then heated and injected into 8 ft x 1/8 in O.D. stainless steel column packed with 60/80 mesh Carbopack B/1% SP-1000. Temperature programmed gas chromatography was performed with a Perkin Elmer Sigma 3 gas chromatograph (3 min. initial hold at 45°C, 8°C/min to 220°C and 15 min final hold at 220°C, detector temp. 250°C, flow rate 40 ml/min of helium. Detection was by flame ionization.

Peak areas determined by the analysis were compared to those obtained from external standards as described above. The external standards were injected in the same manner as described above for the field samples.

The field samples could not be subjected to duplicate analysis since purging used the entire sample. Duplication of results on the external standards was considered satisfactory. The peak areas were within less than 5% disagreement from the mean for six replications, and retention times agreed to within one percent or less.

COMPUTATIONAL PROCEDURE

Data Reduction

As stated previously, the underlying principle and methodology of the concentration profile method has previously been described (5-7). However, a brief description of the computational methods used herein is nevertheless appropriate, especially it will be helpful to describe the source and/or significance of the variables and parameters employed.

The flux of chemical arising from an area source immediately upwind of the apparatus is given by the following data reduction equation developed by Thibodeaux:

$$N_A = -\frac{(D_{A\text{-}Air})^{2/3}}{D_{B\text{-}Air}} S_V S_\rho k^2 (\phi_m^2 Sc^{(t)})^{-1}$$

where:

N_A = flux of chemical A ($ng/cm^2 \cdot s$)
$D_{A\text{-}Air}$ = diffusivity of chemical A in Air (cm^2/s)
$D_{B\text{-}Air}$ = diffusivity of chemical B (water vapor) in Air (cm^2/s)
S_V = slope of the velocity profile plot of velocity (of the wind) vs ln y where y = height off the water in cm. (this slope has units of cm/s)
S_ρ = slope of the concentration profile plot of chemical concentration vs. ln y (this slope will have units of concentration, ng/cm^3)
ϕ_m^2 = diabatic velocity profile correction factor (dimensionless)
$Sc^{(t)}$ = turbulent Schmidt no. for water vapor in air (dimensionless)
k = von Karman constant (k = 0.4, dimensionless)

Of the terms in the data reduction, all except the diffusivities and the von Karman constant were determined from the field measurements (if concentration is a field measurement).

The term $\phi_m^2 Sc^{(t)}$ as it can be applied for water vapor, is approximately related to the Richardson No., Ri, as follows:

$$(\phi_m^2 Sc(t))^{-1} = (1 \pm 50\ Ri)^{\pm 1/2}$$

When the Richardson No. is negative (unstable) then -50 and +1/2 apply. When the Richardson No. is positive (stable) then +50 and -1/2 apply.

The Richardson No., Ri, is a measure of the atmospheric stability and was determined from velocity and temperature profile data as follows:

$$Ri = \frac{g\,(T_{12} - T_{11})\,(y_2 - y_1)}{T_1 \quad (V_2 - V_1)^2}$$

where:

g = acceleration of gravity (980 cm/s^2)
y_2 = height of elevation no. 2 above the surface (cm)
y_1 = height of elevation no. 1 above the surface (cm)
V_2 = horizontal wind velocity at elevation no. 2 (cm/s)
V_1 = horizontal wind velocity at elevation no. 1 (cm/s)
T_{12} = temperature at elevation no. 2 (°K)
T_{11} = temperature at elevation no. 1 (°K)
T_1 = temperature at $y = [(y_2^2 - y_1^2)/2]^{1/2}$ (°K)

The slope S_V can be taken from plots of the wind velocity vs ln y, or from a numerical regression. Similarly, following analysis of the trapped samples, S_ρ can be obtained as the slope of a plot (or from numerical regression) of the concentration vs ln y. In the computations employed in this work, the slopes were determined numerically.

The diffusivity values (for the chemical of interest and for water vapor in air) were not determined from field measurements. Water vapor diffusivity in air is readily

Table 2 - Concentration Profile Data
(Profile No. 4; Example Data)

	Sample Concentrations			
Sampling Height (y) (cm)	Methylene Chloride (ng/cm^3)	Toluene (ng/cm^3)	Temperature ^oC	Velocity cm/s at cm
5.08	0.280	0.584	27.9	198 at 44cm
11.43	0.763	0.345	31.4	220 at 64
24.8	0.371	0.151	31.5	247 at 104
44.5	0.021	0.024	30.8	277 at 184
90.2	0.288	0.001	31.2	292 at 264
181.6	0.203	0.040	31.1	309 at 344

S_v [slope of vel vs ln y] = 52.82 cm/s (correlation coefficient = 0.999)

S_ρ [slope of conc. vs ln (y)]: (ng/cm^3)

For CH_2Cl_2, using 4 of 6 points: -0.179 (Corr. Coef. = 0.901)
For C_7H_8, using 6 of 6 points: -0.159 (Corr. Coef. = 0.909)

Richardson No., Ri, = +0.0187, $(\phi_m^2 Sc^{(t)})^{-1} = (1 + 50\ (0.0187))^{-1/2} = 0.719$

Diffusivity rations: $\frac{D_{CH_2Cl_2\text{-Air}}}{D_{H_2O\text{-Air}}} = \frac{0.120}{0.258} = 0.465;$

Flux: $N_{CH_2Cl_2} = -\ (0.465)^{2/3} \cdot 52.82\ (-0.179)(0.2)^2(0.719) = 0.653\ ng/cm^2 \cdot s$

$$\frac{D_{Tol\text{-Air}}}{D_{H_2O\text{-Air}}} = 0.333$$

$N_{tol} = -(0.333)^{2/3}\ (52.82)\ (-0.159)\ (0.4)^2(0.719) = 0.464\ ng/cm^2 \cdot s$

Table 3 - Summary of Profile Data

Profile	Slopes*		Correlation Coefficient	No. of Points Used
1	CH_2Cl_2	- 0.566	0.972	5 of 6
	C_7H_8	+ 0.101	0.782	6 of 6
	Velocity	+37.14	0.998	
	Ri = + 0.0066			
2	CH_2Cl_2	- 0.093	0.795	5 of 6
	C_7H_8	- 0.008	0.767	4 of 6
	Velocity	+20.94	0.996	
	Ri = + 0.0040			
3	CH_2Cl_2	- 0.214	0.936	6 of 6
	C_7H_8	- 0.006	0.878	5 of 5
	Velocity	+42.49	0.998	
	Ri = + 0.0608			
4	CH_2Cl_2	- 0.179	0.901	4 of 6
	C_7H_8	- 0.159	0.952	4 of 6
	Velocity	+52.82	0.999	
	Ri = + 0.0187			
5	CH_2Cl_2	- 0.097	0.753	4 of 6
	C_7H_8	- 0.047	0.861	5 of 6
	Velocity	+51.17	0.966	
	Ri = - 0.049			
6	CH_2Cl_2	+ 0.092	0.664	4 of 4
	C_7H_8	+ 0.024	0.787	4 of 4
	Velocity	+57.79	0.997	
	Ri = - 0.089			

* Concentration slopes, S_ρ, are in units of ng/cm^3 (ρ_A vs ln y)
Velocity slopes, S_v, are in units of cm/s (v vs ln y)

available from many sources, handbooks, etc. such as Treybal (9). In general, and specifically in the present case, the diffusivity of the chemicals (methylene chloride and toluene) in air were estimated by the method of Wilke and Lee as given by Treybal (9).

Table 2 presents the data for one profile and the calculated values resulting. Table 3 presents a summary of all the profiles and the slopes.

Model Prediction Calculations

Flux of evaporating chemicals can be readily predicted from mass transfer principles if the rate constants can be predicted. Wind tunnel tests, as for example, Cohen et al., (2) will normally attempt to predict a mass transfer coefficient which is related to wind speed, fetch, topography and so forth. At present, the mass transfer predictions suffer from many of the limitations of such predictions as dispersions and so forth, that is, they apply only for certain ideal terrain configurations. Nevertheless, it may be that many waste disposal lagoons conform in many ways to the ideals.

Cohen, et al., (2) is perhaps the latest study to appear in the open literature concerning mass transfer coefficients for wind blowing across lagoons. Cohen's paper suggests the mass transfer coefficient for low-solubility, volatile chemicals can be predicted by the following:

$$K_L = 11.4\ (Re^*)^{0.195} - 5.0$$

where:

K_L = overall liquid phase mass transfer coefficient (cm/hr)
Re^* = roughness Reynolds No. (dimensionless)

The roughness Reynolds No. evaluation requires the estimation of some parameters which are difficult to determine, but the authors suggest an approximation for it as follows:

$$Re^* = \frac{7.07 \times 10^{-3}\ Z_{10} U_{10}^{\ 1.25}}{\nu_a \exp(56.6/U_{10}^{\ 0.25})}$$

where:

Z_{10} = elevation at 10m in cm (thus, Z_{10} = 1000)
U_{10} = wind velocity at 10m elevation (cm/s)
ν_a = kinematic viscosity of air, (centistoke)

Finally, the rate of mass transfer (evaporation of the chemical) from the water surface is estimated as:

$$N_A = K_L\ (\rho_A - \rho_A^*)$$

where ρ_A = concentration of the chemical in water (ng/cm^3)
ρ_A^* = liquid concentration in equilibrium with the actual gas phase concentration of the chemical (ng/cm^3)

It is normally assumed that $\rho_A^* = 0$ when a wind is blowing across a lagoon.

While the simplified flux equation above is adequate for low solubility, volatile chemicals (said to be liquid phase controlled), a more general treatment requires consideration of the gas phase coefficient, k_g, as well, according to the two-resistance theory which is presented in a number of references , including Treybal (9).

One drawback of the Cohen, et al., (2) equation is that it does not have a fetch dependence. The work of Hwang (8) and Sutton (12) suggest that the flux from an area source is a function of the fetch. The gas phase coefficient, k_g, has been found to be a weak function of fetch, such that k_g is proportional to $(\text{fetch})^{-0.1}$ (13). Ongoing work in our laboratories also indicates that the liquid phase coefficient is a weak function of fetch (14). At this point it appears that the fetch correction will be of the order of a few percent, perhaps an increase of less than five (5) percent.

Cohen, et al., (2) determined the mass transfer coefficient for toluene. In order to apply their relation for other chemicals it must be multiplied by a diffusivity correction factor which is a ratio of diffusivities in water to the two-thirds power.

RESULTS AND DISCUSSION

As previously mentioned, the water analyses were as shown in Table 1. The concentration of methylene chloride and of toluene, which were of interest in this study, were both rather low in Pond 3, and were so close to the limit of detection (10 ng/cm^3) that the values became suspect. In Pond 2, the chemicals of interest are high enough to provide for reliable analysis but not nearly high enough to invalidate any assumptions based upon dilute solutions. In Pond 1, the concentration of methylene chloride is similar to that in Pond 2, but the toluene concentration is only about five times the limit of detection and could be suspect.

The flux values determined from the measurements are compared with those calculated by the Cohen (2) model shown in Table 4. Of the twelve determinations (six profiles of two chemicals) there are six (both chemicals in profiles 3 and 4 and methylene chloride in profiles 5 and 6) where the water phase concentration of chemical is suitably high for this study.

Of these six, four show reasonably good agreement, but two do not, they being the unreasonably low flux value for toluene, resulting from profile 3 and the negative methylene chloride flux from profile 6.

The other four determinations show agreement within about a factor of two, which is an accurate as could be expected when comparing models to the turbulent environment.

The results of the other six determinations, that is profiles 1 and 2 for both chemicals and profiles 5 and 6 for toluene are somewhat disconcerting, especially those which show the calculated (Cohen model) flux to be substantially lower than that which was seemingly observed in the field.

In profiles 1 and 6 there are negative toluene fluxes which presumably means toluene was in the air and was being absorbed by the water in the pond. While this might be a satisfactory explanation for profile 1, it doesn't seem reasonable for profile 6, since only a short while earlier, profile 5 at the same location showed an unreasonably high toluene flux away from the pond.

The authors cannot point to any known causes of the several discrepancies. However, possible reasons abound. Perhaps one of the most likely reasons for unreasonable discrepancies would be a non-uniform quality of the sample concentration tubes. These tubes were made up of Tenax porous polymer and silica gel packing inside 1/8" tubes. It is quite impossible to examine a tube and determine that adequate packing is present, or, that if present that it is properly desorbed, and if not, it would have a dramatic effect on the concentration vs. height relationship from which the flux is deduced.

There is also a possibility of leaks between the rotometer inlests and the concentration tube outlets. Even though efforts were made to detect and correct such leaks in the field, there remains the possibility which would again have a pronounced effect on the concentration vs. height relationship.

Finally, the unpredictability of the micro-environment close to the pond surface can certainly introduce seeming inconsistencies in the results. Although a uniform background concentration of chemical would not, presumably, interfere with the concentration profile method of measurement, a background concentration at a waste disposal site would not necessarily be uniform, and background would cause errors in the calculated (predicted) values of flux, since these are based on an assumed zero concentration in the air.

A quantitative determination of the confidence level of the several measurements of the concentration profile method is currently underway, but not yet available (15).

CONCLUSIONS

It has been shown that some of these measurements confirm that secondary emissions from surface impoundments do occur and can be predicted for low solubility, volatile chemicals which evaporate under liquid phase control. Thibodeaux, et al., (5-7) have previously confirmed similar predictability for cases where the gas phase controls.

It is also apparent from this work that the field measurement of volatile chemical emissions from area sources is encumbered by a serious problem of non-reproducibility and that spurious results may be anticipated. The authors feel that the CP method, however, will generally be the method of choice when suitable conditions (such as constant wind speed, a reasonable fetch-to-height ratio of upwind disturbances, etc.) exist for its employment.

Maybe it can be said that this work has accomplished as much to confirm the CP method as it has to confirm the volatilization modesl, even though one would have to address such an issue carefully since it may be confirming two unknowns by mutual comparison.

It is also apparent that some improvements in the measurement methodology may be in order. Indeed, that has been the history of the method during its development. Consistency has improved and operation has become simpler, faster and easier through the evolution of the apparatus and method, from that first used by Thibodeaux, et al., (5-7) through that used in 1981 by Thibodeaux, Springer, Lunney, James and Shen (11), to the present state. The authors are convinced that the method represents state-of-the-art emission monitoring for waste sites where it is applicable.

The authors likewise feel that additional field work will be required before the emission models such as that of Cohen, et al., (2) can be finally confirmed.

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INVESTIGATION OF CLAY SOIL BEHAVIOR AND MIGRATION OF INDUSTRIAL CHEMICALS AT WILSONVILLE, ILLINOIS

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ABSTRACT

Clay soil behavior and migration of industrial chemicals are being investigated at a hazardous waste disposal facility in Wilsonville, Illinois (Macoupin County). The study was initiated after the Illinois Supreme Court affirmed a trial court order requiring the wastes at this site to be exhumed and removed because of their proximity to Wilsonville and the potential for harm to the town from continued operation of the site. The May 1981 order provided a unique opportunity to examine in detail the effects of the wastes on soils below and adjacent to the site and to measure the migration of contaminants from the trenches. Work is currently in progress, but results are not yet sufficient to permit substantial conclusions to be reported. The approach is presented here because it may be helpful to others evaluating hazardous waste disposal sites.

The project provides detailed geologic descriptions of the site, including macro, meso, and micro features and the effects of the waste leachate on these features. A detailed hydrogeologic and geochemical investigation is being carried out, including soil sampling, monitoring wells, piezometers, and hydraulic conductivity measurements. The latter include in situ vertical and secondary fracture flow, laboratory measurements of recompacted samples, and horizontal and vertical tests of undisturbed cores. Measurements of effective porosity will be attempted where feasible.

Detailed investigations of materials present within the landfill trenches include sampling for chemical and physical analyses. Trench materials are being examined with respect to the nature of the backfill and voids, and the condition of the drums and cover. Stereo-pair photography is being used to record trench conditions and correlate them with measurements and notes.

Laboratory studies and chemical analyses are being carried out to support the field investigations.

INTRODUCTION

This study was initiated after the Illinois Supreme Court affirmed a trial court order requiring the exhumation and removal of wastes at a hazardous waste disposal facility near Wilsonville, Illinois (Macoupin County). The reason for the order was the proximity of the site to Wilsonville and potential for harm to the town from continued operation of the site. The order provided a unique opportunity to examine in detail the effects of the wastes on soils below and adjacent to the site and to measure the migration of contaminants from the trenches. Work is currently in progress, but results are not yet sufficient to permit substantial conclusions to be reported. The approach is presented here because it may be useful to others evaluating hazardous waste disposal sites.

The study of the site is a cooperative effort between several agencies and the site owner. The US EPA has supplied a major part of the funding through a cooperative agreement with the Illinois State Geological Survey whose personnel are performing a majority of the work. The Illinois EPA has provided a drill rig and crew for the field studies and is performing organic analyses on soil and water samples from the site. The site owner, SCA Services, Inc., has provided access to the site, safety training, and a substantial amount of the materials for construction of the monitoring wells.

BACKGROUND EVENTS

Earthline Corporation, a subsidiary of SCA Services, Inc., began operating a 130-acre landfill near Wilsonville, Illinois on November 15, 1976. The operation was a trench-and-fill procedure that relied on a clay-till deposit native to the site for natural attentuation of any leachate. A compacted clay liner was used to supplement native till in at least one of the trenches. The company had applied for and received a permit from the Illinois Environmental Protection Agency (IEPA) to dispose of industrial and hazardous wastes at the site. Several months after the landfill was in operation, the citizens of Wilsonville became alarmed at the disposal of hazardous wastes in the proximity of their community. They filed suit to stop the disposal of wastes and to have them removed from the site. A lengthy court battle ensued, and Earthline continued to bury wastes. In March 1982, the Illinois Supreme Court affirmed the May 1981 trial court's ruling that the hazardous wastes buried in the approximately 26 trenches (each 10 to 20 ft deep, 50 ft wide, and 250 to 350 ft long) at Wilsonville must be exhumed and removed from the site. SCA Services, Inc., announced in March 1982 that they were dropping further appeals and would comply with the court order. The preparations began in the summer of 1982, and the actual exhumation and removal process, begun on September 7, 1982, is expected to continue over a 4-year period.

Earlier that year, in February 1982, the IEPA discovered that routine monitoring of wells at the site had shown migration of organic pollutants as far as 50 ft from the trenches in a 3-year period. This discovery was a separate issue from the court proceedings and exhumation order. The migration rates were 100 to 1000 times faster than predicted. Two obvious questions were posed: (1) Why were these organic compounds migrating faster than predicted, and (2) what are the implications to land disposal of similar wastes at other sites? This research project has been designed to provide answers to these and many other questions regarding the impact of land disposal of hazardous wastes, particularly organic liquids.

OBJECTIVES

The project aims to determine why several organic contaminants detected in monitoring wells around the trenches are migrating faster than predicted and what the implications are to land disposal of similar wastes at other sites. An outline of the planned scope of work follows.

Site Characterization

1. A detailed geologic description is to be developed for the site, including macro, meso, and micro geomorphology, soil materials, and hydrogeology.
2. Differences will be noted for laboratory- and field-measured values of hydraulic conductivity.
3. The occurrence and magnitude of secondary hydraulic conductivity or fracture flow will be determined.
4. The effective porosity will be measured for both field-scale and laboratory samples of clay till from the site.

Organic Chemical Effects

1. Measurements will be made of actual migration rates of organic chemicals through soil materials at the site.
2. Studies will be made to determine the effects of certain concentrated organic liquids on permeability.
3. Studies will be made of the effects of organic chemicals on pore struc-

ture, volume, and size distribution in clay from the site.

4. A screening test will be developed to determine the effects of leachate and organic chemicals on clay structure and hydraulic conductivity.

Clay Liner Construction

Sections of Trench No. 24 are lined with a 5-ft layer of recompacted native clay. A study in in progress to determine how the waste leachate affects this liner's ability to retain liquids.

Liquid Level in Waste Cells

The hydrogeology and water balance of the cells are being examined to determine effects of hydraulic head on liner and side wall permeability.

Acid Drainage

The strong acidity and high inorganic salt content of leachate from the adjacent pile of coal cleaning refuse (gob) are being studied with regard to trench conditions and the hydraulic conductivity of trench bottoms and walls.

Condition of Trench Covers

The condition of the covers is being examined as they are removed to determine the role of surface and internal erosion or the effects of settlement resulting from waste subsidence on the water balance of the trenches.

Subsidence

The site is being surveyed at regular intervals to determine the extent of subsidence in the trenches caused by the abandoned coal mine 300 ft below the site.

Condition of Drums and Wastes

The condition of the drums and other wastes is being documented periodically as they are removed from the trenches to help determine the effects of the leachate on the drums and earth materials, the relative leachate strength, and drum life expectancy.

RESEARCH PLAN

MULTIDISCIPLINARY APPROACH

A multidisciplinary/multiagency approach was adopted early in the planning of this project. The coordinated efforts and resources of all the interested parties are expected to produce superior results for several reasons:

1. Access to the site and legal problems are reduced through cooperation with the site operators
2. The number of borings and samples are reduced when the needs of all participants are incorporated into the experimental design.
3. Field personnel and travel needs are reduced by consolidation of efforts.
4. Duplicate testing and analyses are eliminated.
5. Materials required for construction, sampling, and analyses are reduced.
6. Interferences and delays caused by competing priorities are avoided.
7. Stronger conclusions may be drawn because of the contributions of several disciplines and parties.

The multidisciplinary nature of the project and the uncertainty over the potential hazards that would be encountered at the site demanded detailed preparations for the field work. These involved organizational meetings with representatives of the three government agencies and the operators of the site to delineate areas of responsibility, liability, and allocation of resources. Special safety measures prescribed for all onsite staff were: (1) successful completion of an 8-hr first-aid training course, (2) instruction in use of protective breathing apparatus, and (3) a thorough medical examination before beginning field work. In addition, a special first-aid kit has been prepared, and the route from the site to the nearest hospital emergency room has been traveled by the field team.. Protective clothing routinely worn during field work includes hard hat, disposable coveralls, rubber boots, and protective gloves appropriate for the particular task.

Organic vapors are monitored during drilling and other activities, and when concentrations exceed 100 ppm, protective breathing apparatus is worn. Positive pressure breathing apparatus is worn at all times when working in the trenches. Explosive gas mixtures are monitored with an explosive gas meter. A fire truck is onsite at all times. Other routine and special safety precautions are also employed as deemed appropriate.

GEOLOGICAL CHARACTERIZATION

An extensive geologic investigation and description of the site is being carried out to place this site in the proper regional geologic framework and to collect sufficient baseline data for extrapolating the results from our investigation to other sites.

The geologic characterization is being carried out by four principal means: (1) examination of all previously gathered data and information available for the site and for the regional geology, (2) investigation of outcrops and exposures at and in the vicinity of the site, (3) study of the trench walls themselves and backhoe pits at selected locations on and around the site, and (4) study of drill samples collected on and around the site by split spoon, Shelby tube, and Giddings soil tube techniques.

A map of the site study area and the overall drilling plan appear in Figure 1. The drilling includes 11 nests of piezometers and monitoring wells labeled A through K and two profiles of monitoring wells labeled V and W, a total of more than 70 holes. The deepest hole at each nest and profile location was continuously sampled using push tubes near the surface and split-spoon methods for the deeper samples. The samples were logged in the field, preserved in core boxes, and transported to the laboratory, where

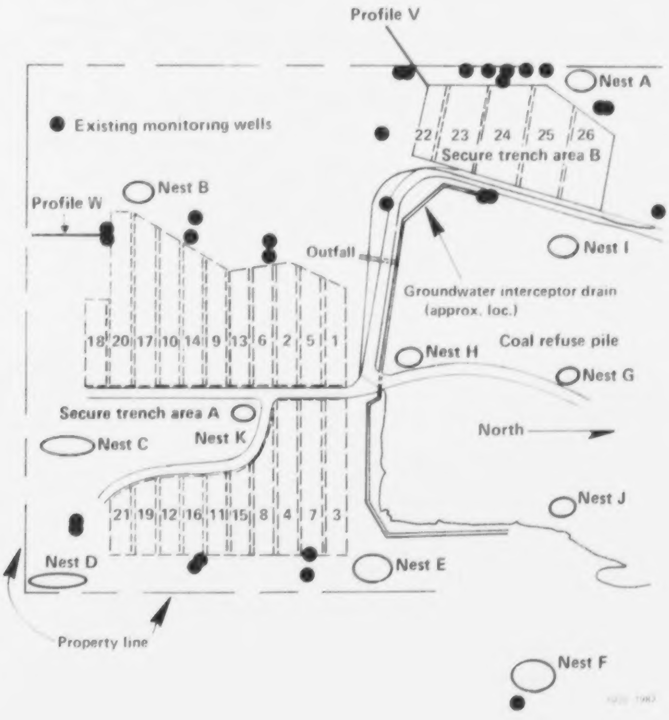
Profile V
Nest A
● Existing monitoring wells
22
23
24
25
26
Secure trench area B
Nest B
Profile W
Outfall
Nest I
Groundwater interceptor drain
(approx. loc.)
18
20
17
10
14
9
13
6
2
5
1
Nest H
Coal refuse pile
Nest G
Secure trench area A
Nest K
Nest C
North
Nest J
21
19
12
16
11
15
8
4
7
3
Nest D
Nest E
Property line
Nest F

Figure 1. Site map showing locations of trench areas and SCA monitoring wells, borings, and observation wells in relation to project well nests and profiles.

detailed sampling and descriptions are being carried out. Sixteen locations at the site were continously sampled for stratigraphic, geologic, and chemical characterization. These 16 holes were commonly 30 to 45 ft deep, but some holes were deeper, including a deep stratigraphic control hole at nest I that was continuously sampled to 92 ft, where bedrock was encountered. Split-spoon samples were also collected at intermittent depths from all the other holes drilled at the site.

Geologic units in the Wilsonville area have been found to extend regionally and undergo areal facies changes. Soil units (pedologic types) in the area also vary areally from one type to another. Changes in geologic materials are directly expressed in the soil types of the area, but these changes have not necessarily been reflected in the agronomic soil classifications.

Special emphasis has been placed on assessing the normal pedologic and geologic features (facies change phenomena, soil horizonation, etc.) in and around the trenches to develop a classification for materials that distinguishes classes of normal and disturbed materials. Assuming that all materials within the trenched area are disturbed to some degree, sites away from the trenches have been sought to establish the normal relationships. For increased confidence in the stratigraphic interpretations, cores from the surrounding region are being collected and evaluated. In addition, more than seven backhoe pits in undisturbed locations adjacent to the trenched area have been examined to complement the study of the exposures produced by the trench excavations.

The geologic characterization will focus particular attention on morphological changes in the soil materials because it is suspected that organic solvents may affect soil structure. Meso- and micro-morphological features will be studied at selected distances from the trench walls and bottoms. These features will be compared with those of normal samples to determine whether the wastes have imparted patterns of change into the morphologies of exposed soils.

Detailed physical and chemical laboratory characterizations are also being conducted on selected samples from the drilling and trench sampling programs. These include particle-size analysis, clay and mineralogical characterization, petrographic (micromorphologic) evaluation, hydraulic conductivity, pore size distribution, surface area, pore volume, moisture/density, and other geologic and engineering tests as appropriate. Complete chemical characterization includes analyses of volatile and semivolatile organics and 30 to 45 inorganic parameters.

HYDROGEOLOGIC/GEOCHEMICAL STUDIES

An extensive hydrogeologic and geochemical investigation of the site is under way and will include borings of 11 piezometer nests (nests A to K, in Figure 1) with three to six piezometers per nest. These piezometers are being used initially for insitu hydraulic conductivity tests at the various depths of the piezometers. Later these piezometers will be used to establish the long-term piezometric surface and in turn the hydraulic gradient and flow across the site. Core samples from these borings will be used for chemical analysis. But water chemistry will not be analyzed because of interference caused by the addition of tap water during the hydraulic conductivity slug tests. In addition, withdrawal of water for analysis is also likely to disturb the piezometric surface measurements.

A separate set of monitoring wells is being constructed for water chemistry samples. These include at least two monitoring wells at each nest and up to 22 wells positioned in a geometric progression from the trenches along two lines. These lines have been designated as V and W in Figure 1. Cores and disturbed samples from the drilling will be subjected to hydraulic conductivity and chemical measurements.

Vertical fracture permeability will be measured by angle drilling at separate locations. Three nests containing three to four holes per nest will be drilled on an angle to intersect possible vertical fractures. Insitu hydraulic conductivity measurements will be carried out, and the results will be compared with previous measurements of vertical and horizontal hydraulic conductivity. Measurements of effective porosity will be attempted where feasible.

The construction of the monitoring wells, screened piezometers, and open-hole piezometers is shown in Figure 2. Monitoring wells were constructed by boring a hole to a selected depth with a rotary hollow-stem auger drill rig. A 2-in.-ID well casing with a slotted well screen was lowered to the bottom of the hole through the hollow-stem auger. All well screens were 2 ft long, and screen and casing materials were stainless steel for monitoring wells. Flush screw joint PVC was used for screened piezometers.

Following placement of the casing and screen, the hollow-stem auger was withdrawn from the hole, and clean medium silica sand was placed to approximately 1.0 ft above the well screen. A plug of 2 to 5 ft of expanding cement was then placed above the sand pack. Expanding cement was used for sealing rather than bentonite to preclude the possibility of cracking because of the presence of organic solvents. A mixture containing 70 % (by volume) clean silica sand and 30% granular bentonite was used to backfill the hole to within approximately 4 ft of the surface. If water was standing in the hole above the lower cement plug at the time of construction, a 5-gal pail of bentonite pellets was occasionally used. To avoid vertical cross contamination, drill cuttings were not used for backfill. The annulus was then plugged to the surface with expanding cement and mounded slightly around the casing to promote drainage away from the well.

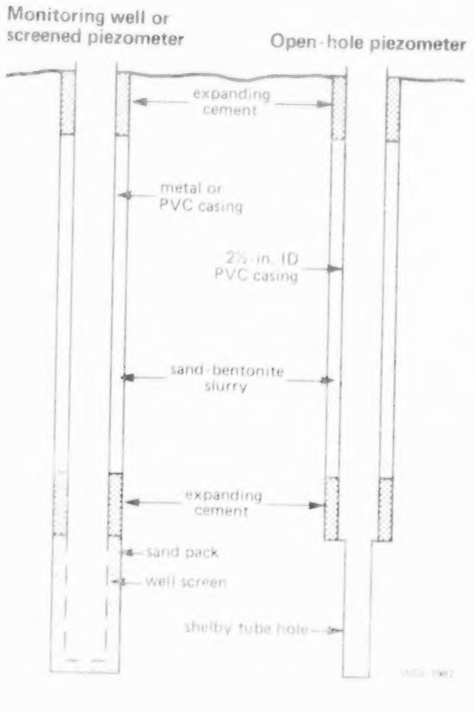

Figure 2. Diagram illustrating construction of monitoring wells, screened piezometers, and open-hole piezometers used at the site.

The open-hole piezometer was constructed in a similar manner. The hollow-stem auger was used to bore to the desired depth. A 2.5-in.-ID PVC glue joint casing was lowered through the hollow-stem auger to the bottom of the hole. The augers were then withdrawn from the hole, the bottom sealed with 2 to 5 ft of expanding cement as a plug, and the hole backfilled as described above. A 2-in. Shelby tube was then lowered through the casing, and a 2-ft long sample was pushed and retrieved with the drill rig, leaving a 2-in. x 2-ft open hole at the bottom. The hole and casing were then immediately filled to the top with water, and the insitu hydraulic conductivity slug test was initiated. The immediate introduction of water applied a positive pressure to the soil, which kept the hole from caving in. Changes in water levels were recorded as a function of time, and the hydraulic conductivity was computed. The Shelby tube sample was sealed and taken to the laboratory for hydraulic conductivity measurements, which can later be compared with field tests at each depth in each nest.

ENGINEERING GEOLOGY INVESTIGATIONS

The engineering geology investigations include: (1) measurement of surface response to potential coal mine subsidence at the site, (2) measurement of settlement and condition of trench covers, (3) determination of physical properties and characteristics of geologic materials composing strata and fill at the site, (4) recording of trench conditions using close-range photogrammetry, stereograms, and mapping, and (5) obtaining and using aerial photography to prepare a model for the final base map of the site and to interpret geologic features.

Measurement of surface and near-surface response to subsidence of the underground coal mine workings involves careful construction of monuments and precise surveying measurement. The construction of the survey monuments and settlement probes is illustrated in Figure 3.

Because of the anticipated small movements likely to be measured at the site, surveying monuments must be constructed in such a manner that movements of the monuments are those that reflect movements of the target strata and are not complicated by other forces such as shrink-swell soil, freeze-thaw phenonema, groundwater fluctuations, vehicular traffic, and other possible earth movements. Third order or better surveys are necessary to assure the accuracy needed for recording subtle movements of the monuments.

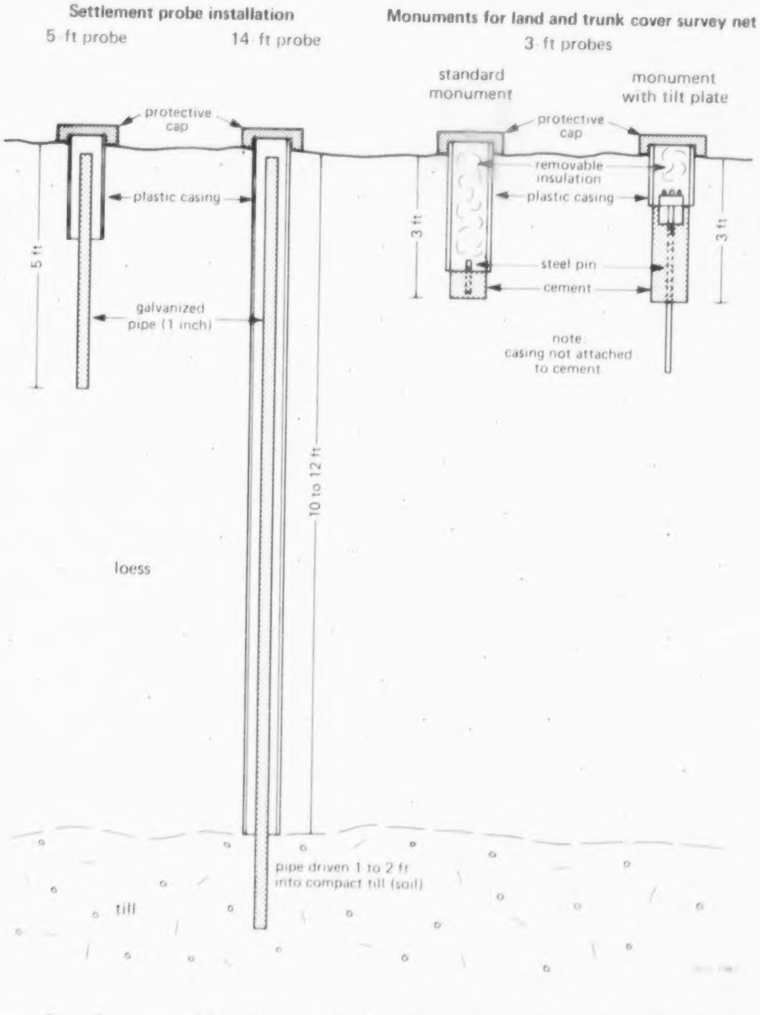
Settlement probe installation
5-ft probe
14-ft probe
Monuments for land and trunk cover survey net
3-ft probes
standard monument
monument with tilt plate
protective cap
protective cap
plastic casing
removable insulation
plastic casing
5 ft
3 ft
3 ft
steel pin
cement
galvanized pipe (1 inch)
note: casing not attached to cement
10 to 12 ft
loess
pipe driven 1 to 2 ft into compact till (soil)
till

Figure 3. Diagram illustrating the construction of the settlement probe and monument installations used at the site.

Measurement of trench cover settlement will likely be less accurate than that proposed for surface response to coal mine subsidence. The principal problem is that the covers are approximately as thick as the frost penetration expected at the site; consequently, founding a survey monument below the frost penetration depth would have meant boring into the wastes--an undesirable prospect for various reasons. Movements of monuments on the trench will therefore be subject to nonsystematic errors. Further study is under way to mitigate this problem.

Trench cover settlement data from this phase of the study will provide unique information in this regard. These data will be of particular value in designing limited-infiltration, multiple-layered earth trench covers that appear likely to be sensitive to settlement stresses.

The condition of the cover is important as a potential failure mechanism because any reduction in the effective thickness of the soil cover by external or internal erosion or by cracking because of waste subsidence would increase the amount of water percolating into the waste cells. The amount of leachate released from the cells may be due to increased hydraulic head on the bottom and side walls of the trenches. The condition of the cover will be studied in place and as it is removed to determine the extent to which external examination can identify such problems.

The number and condition of the drums and their contents relative to other wastes will be investigated during the waste removal process. This information will help interpret the observed effects on soils in the context of predicting whether maximum leachate strength has occurred. The information will also help estimate the effective service life of steel drums in landfill cells in this environment.

In conjunction with the trench investigations and sampling, the condition of drums and backfill in the trenches will be recorded by still photography, employing techniques for stereographic recording. Stereograms have been made of the features in the surface of one trench cover and are being applied to studies of features in the trenches.

To extrapolate better the measurements taken in the trench and to record the location of samples taken, a 2-ft aluminum cube with holes drilled on centers will be incorporated into stereographic photographic pairs and triplicates. Plumbing and orientation of the cube will enable researchers to orient directions in space. Negatives can be placed into a stereoplotter to make exact measurements of thickness and area. In addition, where joints occur, measurements of slope magnitude and direction can be made where the use of a clinometer would be clumsy or impractical.

Aerial photographs will be obtained over the study site for use as a base map and for interpretation of geologic features. An effort will be made to differentiate bedrock from glacial features. Lineaments of unknown origin will be examined by field studies. We are attempting by this study to incorporate into waste disposal site selection the current photointerpretation techniques used for mineral, oil, and gas exploration, and structural geologic mapping.

LABORATORY INVESTIGATIONS

Hydraulic Conductivity Studies

Laboratory studies are designed to provide data to help interpret field measurements and observations. These studies involve laboratory measurements of hydraulic conductivity using selected aqueous and organic liquids. These results will be compared with those obtained in the field. In addition, we will measure the effects of varying concentrations of an organic solvent (such as methylene chloride) on hydraulic conductivity. These data will help interpret the insitu hydraulic conductivity measurements and correlate laboratory measurements with field data for predictive purposes.

Additional laboratory studies will include determination of moisture release curves, measurements of effective porosity, and delineation of unsaturated flow characteristics of soil materials from the site. These measurements will be carried out in aqueous media and as a function of organic solvent concentration.

Screening Test For Leachate Effects On Clay

A related question that this project will attempt to answer is how can the potential for clay liner failure from leachate attack be identified at operating and closed facilities. Because it is difficult to predict leachate composition (particularly for mixed-waste facilities), and because leachate composition changes gradually with time, it is possible that incompatible waste/clay liner combinations may fail to be identified during the design of the facility. If reference samples of the clay are taken during construction and preserved, then testing can be conducted during facility operation or after closure using samples of leachate taken at those times. If appropriate tests have been previously identified and correlated with the behavior of clays in the field, then the potential for clay liner failure can be evaluated with greater confidence than is possible during the design phase of a facility. In this project, samples of currently produced leachate, affected clays from the facility, and unaffected clays from outside the facility are available. This situation presents a unique opportunity to evaluate the feasibility of developing a screening test for clay liner failure.

Measurements of the viscosity and filtration rates of leachate-clay suspensions will be evaluated for use as a screening test to identify leachate effects on the hydraulic conductivity of clays and as aids in interpreting the field observations and measurements. If the results of these studies correlate with the effects observed in the trenches, these tests could be used for post-closure tests at other facilities.

We anticipate that organic solvents will play a major role in the migration of pollutants through earth materials at the site. The reason is that large increases in permeability to organic liquids in landfill liners could possibly develop by at least two conceivable mechanisms: (1) interlayer collapse of clay minerals because of dehydration, or (2) flocculation resulting from changes in surface properties of clay minerals. A test of the cause of these failures is essential. If the sudden increase in permeability is due to flocculation of clay particles, a viscosity test could provide an excellent means of quantifying the effect. Changes in viscosity of clay suspensions can be related directly to degree of flocculation of the suspension. A viscosity test will allow a rapid screening of different chemicals, give a quick test of synergistic interaction between chemicals, and provide an evaluation of any corrective actions. Viscosity tests can be run on all earth materials, and experimental consistency can be maintained by adding water or clay to achieve a comparable starting viscosity for each test.

A measure of the filtration rate of liquids from dilute suspensions of clay materials could also be used to study the failure of clay liners. A filtration rate experiment is probably a better simulation of the response of a clay liner material, but the test cannot be used to distinguish between permeability changes resulting from flocculation and those owing to shrinkage of the clays caused by organic-induced dehydration and interlayer collapse of clays. Once the mechanism of failure is clarified, a filtration rate measurement could represent a rapid method of screening numerous chemicals and clays.

If part or all of the increased permeability (syneresis effect) that is due to organic chemicals results from shrinkage of clays (because of dehydration and replacement of associated interlayer water), this phenomenon should be measurable by X-ray diffraction. This experiment would be carried out using smectite clay and indigenous materials. Appropriate quantities of organic chemicals will be added to the test samples, and X-ray diffraction will be used to check replacement of intercrystalline water. If the rate of replacement is determined to be a significant factor, this variable will also be measured with diffraction techniques.

All of the above field and laboratory data will serve as input for computer models that will be used to attempt quantitative predictions of water balance, ground-water movement, and pollutant migration across the site. Predictions made with the computer models will be compared with actual field measurements, and the implications of predicting future migration of contaminants from the site will be discussed. Discrepancies between predicted and actual observations will be interpreted with respect to the design of earthen liners and covers for landfills, and with regard to the implications to the permit process for new waste disposal sites and post-closure processes for existing sites.

CURRENT STATUS

The major efforts of this project to date have been the installation of wells and the collection of samples outside of the disposal pits. Soil borings and installation of monitoring wells have been completed. Analyses of water, leachate, and soil samples are under way. Preliminary examination of samples from the soil borings and observations made in backhoe pits on and around the site indicate that sandy layers within the clay till are not continuous and thus cannot account entirely for the observed contaminant migration. The significance of discontinuities and joints exposed in the till by backhoe pits remains to be determined. With the decrease in field work because of winter weather, laboratory studies of hydraulic conductivity, contaminant adsorption, and screening tests for leachate attack on clays are being initiated.

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GROUNDWATER AND LEACHATE PLUMES:
A MODEL STUDY

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ABSTRACT

A TRD has been prepared to aid in the evaluation of permit applications as they deal with leachate plume migration and mixing. The document describes the development of a variety of computer programs, nearly all of which are designed for hand-held calculators and microcomputers. The programs permit prediction of leachate plume migration and groundwater recharge. The document also contains discussions of sorption, case histories, and a field study.

INTRODUCTION

This paper describes a technical resource document (TRD) being developed to assist U.S. Environmental Protection Agency (EPA) permit writers in evaluating permit applications for hazardous waste storage, treatment, and disposal facilities. The document describes a method for predicting leachate mixing and movement in ground water; it has been submitted to EPA and is expected to be released for public comment in the near future.

In addition to the TRD, several projects are under way that will eventually support additions and revisions. These supporting projects are conducted through the National Groundwater Research Center and are sponsored by the Municipal Environmental Research Laboratory, Cincinnati, Ohio, and by the R.S. Kerr Environmental Research Laboratory, Ada, Oklahoma. The projects include:

1. A vertical cross-section model of a leachate plume,
2. A groundwater recharge model,
3. Field tests of dispersion coefficient estimates,
4. Measurement of adsorption phenomena and incorporation into mass transport equations,
5. Use of a case history to test the TRD, and
6. Conversion of the model from VS BASIC to FORTRAN.

TECHNICAL RESOURCE DOCUMENT

The TRD addresses two major questions:

-- How much will concentrations of leachate contaminants be reduced after mixing with ground water?

-- In what direction will a leachate plume travel and how will its configuration change along the travel path?

Permit applicants are assumed to use a variety of methods for predicting the effects of a disposal site on ground-water quality and to need a method for screening these predictions to identify potential errors and the need for more detailed examination. To accompish this task the TRD will provide a variety of predictive techniques ranging from simple to complex. The document is a primer on leachate movement and mixing. A variety of sophisticated models are available elsewhere for use by those with a strong background in hydrogeology.

This report summarizes the TRD (Pettyjohn et al., in press), and includes work completed, in progress, and soon to be undertaken.

Because our charge from EPA implied a series of less-complicated techniques, the literature was searched for an adequate chemical transport equation that could be modified to suit these specified conditions. The fundamental equation on which our analytical techniques are based was described by Wilson and Miller (1978) as follows:

$$C = \frac{f'm \exp{(x/B)}}{4\pi n \sqrt{D_x D_y}} W(u,r/B) \qquad (1)$$

where: C = the predicted concentration of a contaminant

m = the aquifer thickness

f'm = the mass injection rate of contaminant

D_x & D_y = longitudinal and transverse dispersion parameters

n = porosity

W(u,r/B) = well function for leaky aquifers described by Hantush (1956 and 1964).

Some obvious oversimplifications exist with this model -- the lack of a natural recharge term for example. But it was chosen because it is simpler and has fewer parameters than the other equations examined. The simpler solution lends itself better to developing a nomograph and user-oriented calculator and computer programs. The most significant consequence of adopting these simplifying assumptions is that the user cannot predict changes in contaminant concentration with depth because the model is two-dimensional and averages concentration over the entire thickness of the aquifer. This deficiency is being remedied by development of the plume cross-section model discussed later in this paper.

The techniques used to predict leachate plume migration and mixing were divided into three stages. The first is represented by a nomograph that can be used to calculate the centerline concentration in a plume at some designated time and distance along a flow path that begins at the point source. The system is not designed to map a plume (Figure 1). The second relies on a programmable calculator. The calculator code allows modeling of dispersion, retardation, and radioactive decay. Repeated calculations will lead to concentration mapping. The program was devised for a Texas Instruments TI-59 hand-held calculator. The third and most complete technique is a computer program developed to calculate plume concentration by means of an IBM 370 computer. The program is written in VS BASIC for use with a TSO interactive facility and can calculate and display concentration values for a specified time at selected points on a grid map. An output example is shown in Figure 2.

These techniques, with examples, have been described and discussed in detail by Pettyjohn et al. (1981, 1982) and Kent et al. (1982).

VERTICAL CROSS-SECTIONAL MODEL OF A PLUME

The model in the TRD predicts the average concentration at each point in a plan view of the contaminant plume. This concentration is averaged over the entire depth of the plume. In practice, concentrations will vary with depth at each point. An effort is under way to develop a model for vertical distribution of contaminant concentrations to supplement the horizontal distribution model in the TRD. Instead of being based on a two-dimensional solution (Equation 1) of the conservation of mass problem, the vertical cross section model will be based on the full three-dimensional solution.

The differential equation that describes the conservation of mass in a homogeneous aquifer with uniform, steady flow in the x-direction can be written as

$$R_d \frac{\partial C}{\partial t} + V \frac{\partial C}{\partial x} = D_x \frac{\partial^2 C}{\partial x^2} + D_y \frac{\partial^2 C}{\partial y^2} + D_z \frac{\partial^2 C}{\partial z^2} - R_d \lambda C \qquad (2)$$

where:

C = the component mass per unit volume of fluid phase,

D_x, D_y, D_z = the dispersion coefficients in x, y, and z coordinate directions,

V = the seepage velocity (Darcy velocity is a flux: seepage velocity is Darcy velocity divided by effective porosity.

R_d = the retardation coefficient, and

λ = the first order decay constant.

The retardation coefficient accounts for the adsorption/absorption of the component on the solid matrix assuming a linear adsorption isotherm. The retardation coefficient used in Equation 2 is defined as

$$R_d = 1 + \frac{\rho_B}{\theta} K_d \qquad (3)$$

where:

K_d = a distribution constant that describes the linear relationship between concentrations on the solid matrix and in the liquid phase;

ρ_B & θ = bulk density and porosity of the porous medium, respectively.

Equation 1 is a vertically averaged solution -- that is, the equation is integrated over the saturated thickness, and the resulting two-dimensional solution describes concentrations in a horizontal plane as shown in Figure 2. This is the model described by Pettyjohn et al. (in press).

A horizontally-averaged solution to Equation 2 would represent a line source of infinite length located on the water table perpendicular to the direction of ground-water flow. The coordinate system is shown in Figure 3. An interactive or command language program has been written for both the steady-state and transient solutions. A nonuniform source loading has been incorporated using multiple source rates and superposition in time. The program is menu-driven, and the user can modify any or all of the input variables using two-keystroke commands.

As presently written, the solution is for aquifers of infinite thickness or for regions of confined aquifers that are near the source where the plume has not penetrated the entire saturated thickness. An option has been added to include solutions for aquifers of finite depth by using superposition in space (i.e., image wells). Computer codes are in FORTRAN and BASIC. A code for the TI-59 programmable calculator is also available.

NATURAL GROUND-WATER RECHARGE MODEL

One of the major unknowns in any ground-water study is the rate at which water infiltrates the land surface and percolates to the water table. In many ground-water pollution studies, recharge is important because the infiltrating fluid leaches water-soluble compounds from a disposal site to form a leachate plume. Conversely, recharge may be a mechanism that tends to dilute a plume, change its geometry, or influence the vertical distribution of contaminants. Several ground-water quality transport models require recharge as an input parameter.

Recharge can be determined or estimated by a number of methods, including stream hydrograph separation, flow-net analysis, water-table fluctuations, infiltration rings, etc. Some tests (such as infiltration rings) are highly site-specific, whereas others (such as stream hydrograph separations), are more regional. Both local and regional techniques have shortcomings.

The method we developed is regional, but it may provide an estimate of monthly and annual recharge rates. The method is based on stream hydrograph separation techniques and is described in detail by Pettyjohn and Henning (1979).

Ground-water recharge eventually discharges into streams or is removed by evapotranspiration. A long-term balance exists between recharge and discharge, and in an unstressed aquifer, the amount of water continually in storage is nearly constant. The recharge program calculates effective ground-water recharge rates. The effective recharge rate is the total quantity of water that originates from downward infiltration to the water table and upward leakage (if any) from deeper zones to a shallow or surficial aquifer and then eventually finds its way to a nearby stream. Effective recharge is synonymous with ground-water runoff. The effective recharge is less than total recharge because the latter is depleted -- largely by evapotranspiration, and to a smaller extent by pumping.

The recharge methods (fixed interval, sliding interval and local minima) generally provide two calculations that are similar, whereas the third may be substantially different. This result reflects the streamside geology. Most commonly, values for the two closest calculations are averaged.

The data set needed for the analysis can be obtained from the U.S. Geological Survey, which annually publishes stream flow and chemical quality data for each state. The data are listed by water year, which begins October 1. Water year 1980, for example, started on October 1, 1979, and ended on September 30, 1980.

Presently the program is written in FORTRAN for use on an IBM 370. The code is being written in BASIC for a microcomputer. An example of one of the output options, using a VERSATEC printer/plotter, appears in Figure 4.

DIMENSIONAL ANALYSIS OF SOLUTE PLUMES IN GROUNDWATER: FIELD-SCALE EXPERIMENTS

The dispersion coefficients (Dy, Dx, and Dz in Equations 1 and 2) significantly affect the predicted plume shape and concentration distribution within the plume. Most of the available values for dispersion coefficients are based on laboratory studies, and considerable controversy exists over values of the coefficients under field conditions. Because of the significant effect of the value of the dispersion coefficient on model predictions, we have arranged to compare literature values with values from a carefully controlled field test in a similar material. This test will use dye tracers and a series of injection and observation wells to evaluate the flow system. Although the dispersion coefficients will be applicable only to the system studied, the magnitude of the difference between literature and field values will also be a basis for determining the need for similar work in other hydrogeologic settings.

The field investigation is being conducted by the Illinois State Water Survey under the leadership of T.G. Naymic. The site for the experiments, located in Sand Ridge State Forest in west-central Illinois, has been in use since February 1982. Full cooperation was obtained from the owner (Illinois Department of Conservation), and three well drilling contractors installed wells to sample the aquifer. Sixteen wells are in place at the experiemental plot.

In March 1982, the first three wells at the site were installed 300 feet apart in a triangular pattern. Water levels in these wells have been measured every 2 weeks since April 1982 to monitor the ground-water gradient and flow direction. These data were used to establish the proper location of three additional wells that lie along a flow line.

A preliminary tracer experiment was conducted in August using only four wells spaced 20 feet apart. The purpose of this experiment was to gain information on solute travel times, but the tracer was not detected in any of the down-gradient wells. A flow direction shift caused by irrigation wells was determined during August, but the main problem was a lack of control on the system brought about by an insufficient number of observation wells.

Subsequently, 10 additional wells were installed near the source well. During the drilling of one well using a hollow-stem auger, split-spoon aquifer samples were collected. The interval of the aquifer that will receive the tracer consists of 11 feet of windblown sand that is underlain by 9 feet of fluvial sand and gravel. The hydraulic conductivity in the lower sand and gravel (1600 gpd/ft^2) was obtained from sieve analyses and was four times greater than that of the upper sand (400 gpd/ft^2). The results of porosity experiments showed higher actual (0.29) and effective (0.28) porosity in the upper unit than in the lower. Actual and effective porosities in the lower unit are 0.25 and 0.23, respectively.

Other tests included two adsorption experiments designed to measure the amount of adsorption of the tracer (Rhodamine WT) on the aquifer materials and the drilling fluid (Revert). No adsorption was detected on either experiment.

A continuous water-level recorder was installed in a 6-inch-diameter observation well approximately 3 feet from the source well. These two wells and the well from which the aquifer samples were taken will serve as the three source wells for another experiment, which will be conducted in 1983.

After the water-level recorder was installed, a water injection test was conducted using the current source well as the injection well. Native ground water (400 liters) was used to create a local groundwater mound around the source well. The purpose of this test was to check the hydraulic connection between the source well and the nearby observation wells. The water-level rise in the wells screened only in the lower sand and gravel unit was twice that of the wells screened only in the upper sand unit. As a result of this biased response, future tracer injection volumes will be kept to a minimum in order to keep the injection coordinates the same for both units.

Currently, water samples are being analyzed monthly at the site with the hope of directly correlating water-level changes (recharge events) to changes in natural quality. Regional recharge rates, based on the model described earlier, are also being examined.

Throughout the project, model development has continued in preparation for analyzing the results of the tracer experiments. Computer codes have been written to solve the one-dimensional transport equation for several conditions. For example, with the measured water levels and tracer concentrations, the physical and chemical characteristics of the site are estimated and used to predict the response of the system at down-gradient wells. A two-dimensional numerical model has been designed for the Sand Ridge site.

FATE AND TRANSPORT STUDY

This segment of the investigation reviews the methods that have been used to quantify the movement of pollutants in the subsurface in relation to the adsorption characteristics of the subsurface solids. This study has two primary goals: One is to evaluate methods for determining adsorption isotherms, and the second is to examine methods for incorporating adsorption phenomena into the mass-transport equation.

Primary emphasis in the literature is on the adsorption of nonpolar organic compounds on soil organic matter. With the exception of certain agricultural chemicals, little attention has been given to polar-organic compounds or to the adsorption on clay or amorphous hydroxides of iron, manganese, and aluminum.

The two main approaches for indirectly determining adsorption isotherm coefficients for hydrophobic, nonpolar compounds are the inverse correlation between adsorption and solubility and the relation of octanol-water partition coefficients to adsorption. See Kenaga and Goring (1980) for details. Considerable caution must be exercised in the use of these formulas because different assumptions are made for each equation. Quantative relationships are generally derived by lease squares fit of experimental data. Also, not all organic materials behave in the same way or even in a predictable manner. For some organic compounds, the solubility equations may give completely different adsorption coefficients from those derived from the octanol-water coefficient technique.

Present work attempts to establish the assumptions and applications of the various methods for indirectly determining the adsorption coefficient. Concurrently, work is proceeding on the evolution of mass tansport equations using adsorption coefficients.

CASE HISTORY STUDY

An examination of published materials and an evaluation of data found in files of consulting firms regarding ground-water contamination cases have revealed some interesting but disturbing points. The examination of case histories included several hundred examples. Unfortunately, many regulatory agencies have assumed that the literature contains an abundance of cases that describe leachate plume mixing and migration in considerable detail. Because of this assumption, many administrators believe it is no longer necessary to conduct field studies. But examination has shown that despite the hundreds of published examples, probably fewer than a half dozen contain sufficient information to make a prediction. In nearly every case, only enough information has been collected to show that a problem actually exists, and mere guesses have been made on the properties required to make a prediction. The significance of this finding is clear: More field studies must be undertaken where such parameters as dispersion, adsorption, and the areal distribution (both vertically and horizontally) of water-bearing strata are examined in some detail.

MODEL OF A CASE HISTORY

The model applications described in the TRD were tested using the chronium study on Long Island. The Babylon landfill on Long Island also was chosen to extend the model approach to other studies. This study provided an opportunity to calibrate the model using data representing different depths. Calibration techniques included adjustments in velocity, mass rate, and thickness (vertical mixing).

A complete set of water quality measurements from the vicinity of the Babylon landfill was obtained and entered into a central computer data file. The data represent three depths from which samples were collected and subsequently analyzed. Thus a three-dimensional analysis of the plume geometry can be represented by the three depth intervals.

The plume was described at three separate depth zones (a, b, and c). Each zone was set at a thickness (m) of 25 feet with each representing the sampling interval of the wells in the monitoring well nest at the site (see Figure 5). Selected chemical constituents such as chloride were contoured for each depth horizon. These data were then used to help calibrate the plume model.

The simulation included nine starting times, with a different mass flow rate for each time period. The initial starting times and mass flow rate were estimated by calibrating a model with measured chloride concentrations along the centerline of the plume. The most successful calibration resulted during a simulation of chloride movement in zones b and c.

The use of a mixing thickness (m) for depth zones b and c provided another dimension in model calibration, which can be used with the modeling procedures described in the original manual.

FUTURE OBJECTIVES

In addition to tasks described above, several others are in progress. When completed, all of the tasks will be described in separate chapters of the original leachate prediction manual. These include the following:

1. Conversion of the transport program from VS BASIC to FORTRAN language.
2. Modification of the program to include a plume cross-sectional output, superposition of several sources for different time periods, and superposition of a subdivided source.
3. Development of a users manual for the FORTRAN version.
4. Conversion of the vertical model from FORTRAN to BASIC.
5. Development of a technique to examine the effect of natural recharge on a plume.
6. Completion of a computer code for recharge mound geometry to be used on handheld and microcomputers.
7. Development of stochastic models to gain some insight into the effects that errors or uncertainties in site characterization have on predicted leachate plume concentrations. Deterministic models such as those discussed previously provide a specific result or set of results for the specified input parameters that are assumed to be exact. In practice, these input parameters provide the physical and chemical characteristics of the site and the contaminant; but they are seldom, if ever, known exactly. Parameters such as porosity or hydraulic conductivity may represent average values for a very heterogeneous system. Dispersion coefficients incorporate a variety of mechanisms that can result in the spread of a contaminant: but values of these parameters might only be guessed within an order of magnitude. These uncertainties are not reflected in the results of a deterministic model.

Fairly simple statistical methods are being evaluated for possible use in conjunction with the deterministic models included in the manual. The objective of this effort is to quantify the range of probable concentrations that might be expected at a particular time and position in a leachate plume. Rather than predicting a single value, the attempt is to produce an expected value and an associated confidence interval that reflects the uncertainties or errors in the input data.

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PROCEDURES AND TECHNIQUES
FOR
CONTROLLING THE MIGRATION
OF LEACHATE PLUMES

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ABSTRACT

The problem of leachate plume management has been aggravated, to some extent,by a lack of understanding of plume dynamics and the various remedial options available. This paper summarizes information in the areas of leachate plume dynamics and plume management alternatives. The paper describes factors that affect leachate plume movement and key considerations in delineating the current and future extent of the leachate plume. Four technologies for controlling the migration of the plume are also discussed: (1) groundwater pumping involves extracting water from or injecting water into wells to capture a plume or alter the direction of groundwater movement; (2) subsurface drains consist of permeable barriers designed to intercept groundwater systems; (3) barriers consist of a vertical wall of low permeability materials constructed underground to divert groundwater flow or minimize leachate generation and plume movement; and (4) in-situ treatment methods which biologically or chemically remove or attenuate contaminants in the subsurface.

INTRODUCTION

Cleaning up the thousands of hazardous waste release sites identified across the U.S. is a serious environmental challenge to the Nation. Of particular importance is protecting and cleaning up contaminated groundwaters that now serve or could serve as drinking water supplies. The problem of leachate plume management has been intensified to some extent by a lack of understanding of plume dynamics and the various site remediation options available. Generally, methods for controlling the migration of a leachate plume **fall into one of four categories--groundwater pumping, subsurface drains, low permeability barriers, or in-situ** treatment. The purpose of this project, then, was to prepare a reference manual on factors that affect the movement of hazardous leachate plumes, and considerations necessary to develop sound plans for managing leachate plumes. The purpose of this paper is to present an overview of the manual's contents.

PLUME DYNAMICS

The simplest type of leachate plume, in terms of plume movement, is one which mixes with groundwater and moves at the same rates and in the same directions as groundwater. In this case, plume velocity (ignoring attenuation and other geochemical factors) can be expressed by Darcy's Law:

$$V = K\ i/n = Ti/bn$$

where

V is the velocity of the plume

K is the effective permeability or hydraulic conductivity of the aquifer

i is the hydraulic gradient or the slope of the water table or the potentiometric (pressure) surface

n is the porosity of the aquifer

T is the transmissivity of the aquifer or the aquifer's ability to transmit water to wells

b is the saturated thickness of the aquifer through which groundwater flows.

Thus, the velocity of a plume moving with groundwater will be directly related to the transmissivity and the gradient, and inversely related to the saturated thickness and the aquifer's porosity.

The direction of movement of simple plumes is controlled by the gradient of the potentiometric surface. In unconfined aquifers, this gradient commonly follows the surface topography. The gradient, however, can be affected by a variety of hydrologic and geologic factors. Some of those factors include:

- **Aquifer Geometry**--The shape of the water bearing zone through which contaminants flow. For instance, a "shoestring" aquifer formed by buried stream deposits can channel contaminants in a sinuous path from a site independent of surface topography.
- **Aquifer Uniformity**--The consistency of the hydrologic properties of the aquifer. For example, lenses of higher permeable materials can cause contaminants to break off from the main body of the plume and migrate independently.
- **Geologic Discontinuities**--Faults, fractures, bedding planes, joints, and other planes of greatly different permeability. For example, sealed (low permeability) fault planes can restrict plume movement in a given direction while open (high permeability) fault planes can channel the plume in a new direction.
- **Hydrologic Barriers**--Areas of recharge or discharge which control potentiometric gradients.

In addition to hydrogeologic factors, man-made alterations to surface or subsurface conditions can also affect the direction and rate of leachate plume migration. For example, plume movement can be redirected by the presence of pumping wells, sewer lines, mines, canals and impoundments, tunnels, construction activities, and buried foundations. The cumulative effect of these and other factors can make predicting plume migration patterns an extremely complex task even for water soluble plumes that move with groundwater flow. Consequently, it is imperative to delineate plumes on a site specific basis.

PLUME DELINEATION

Before the options for leachate plume management at a given site can be developed, it is essential to know the spatial dimensions of the plume. There are a variety of direct and indirect methods for obtaining data on a plume's dimensions including:

- Aerial image interpretation
- Hydrogeologic investigations
- Geophysical investigations
- Groundwater sampling
- Hydrologic (computer) modeling.

Aerial imagery refers to pictorial representations produced by electromagnetic radiation that is emitted or reflected from the earth and recorded by aircraft mounted sensors. The simplest, most common kind of imagery is the photograph, which uses only the visible part of the electromagnetic spectrum.

The most common type of image outside of the visible spectrum is the infrared image. Infrared images indicate areas that are hotter or cooler than the general surroundings such as areas of dead or stressed vegetation. If historical aerial imagery is available, comparisons between new and old imagery can indicate changes in an area that may be due to leachate migration. For example, the gradual development of a barren area in a forest near a disposal site may indicate the presence of hazardous leachates.

A hydrogeologic site investigation typically consists of installing a number of wells and conducting tests which characterize the aquifer's ability to store water (storativity) and transmit water (transmissivity). Three types of tests can be used to obtain this information:

- **Pumping Tests**--During a pumping test, one well is pumped and the decline in the water level in the aquifer (i.e., the drawdown) is monitored in other wells over time, generally from a few hours to over a week depending on the aquifer. Pumping tests are applicable to both confined and unconfined aquifers and are the most common type of aquifer test used.

- **Slug Test**--In a slug test, water is typically injected into a well and the decline in the water level is monitored over time. Slug tests are used most commonly in shallow, unconfined aquifers.

- **Pressure Tests**--In a pressure test (also called a packer test) a zone of the aquifer is isolated and water is injected into the formation while the injection pressure is monitored. Pressure tests are generally used only in bedrock aquifers.

In addition to conducting aquifer tests, a hydrogeologic investigation should also provide detailed information on site geology and pedology from well logs as well as document the presence of leachate seeps, geologic discontinuities, and discharge and recharge barriers.

The well logs obtained in the hydrogeologic investigation will provide excellent data on the subsurface geology at discrete points. However, this information may not be sufficient (unless a large number of borings are taken) if the geology of the site is highly variable. In this case, a geophysical survey of the site can provide a cost effective solution. The geophysical methods most commonly used in site investigations are resistivity, seismic, metal detection, and radar. With proper application of geophysical survey methods, the lateral and vertical extent of the plume can be determined, changes in contamination with depth can be approximated, depth of bedrock can be established, and metal drums or debris can be located.

The most direct means of delineating a leachate plume is by groundwater sampling. Typically, the wells installed during the hydrogeologic investigation are also used for obtaining samples of the contaminated groundwater. However, obtaining valid groundwater chemistry data is extremely difficult because of the large number of variables involved. Some of the factors that can affect the validity of groundwater sampling results are outlined in Table 1. The results of the chemical analyses of these samples can be plotted on a site map and contoured in much the same way as water table and land surface elevations. These concentration contour maps for individual chemical contaminants can then be used to ascertain plume movement directions, which can be critical in cases where the plume does not follow groundwater flow paths.

Groundwater models have been used to evaluate the extent and expected movement

TABLE 1: FACTORS AFFECTING THE VALIDITY OF GROUNDWATER SAMPLING RESULTS

Influencing Factor	Inherent Problems
Well Installation	Samples can be contaminated by well material or equipment used to install the well.
Well Purging	Analytical results can be skewed if the sample obtained is stagnant water (insufficient purging) or is diluted (excessive purging), or if the time between purging and sampling is too short or too long.
Sample Acquisition	The methods used to extract the water from the well (e.g., pumping, bailing) and place the water in the sample container can change the chemical properties of the sample (e.g., pH, volatile organic content).
Sample Preservation and Holding	Samples that are not preserved properly (e.g., through refrigeration or pH adjustment) or that are held too long prior to analysis can undergo chemical changes.
Sample Analysis	Rigorous laboratory controls are required to preserve sample integrity, especially when working in the parts per billion range. Even so, common laboratory contaminants (e.g., phthalates) may adversely affect sample analysis.

of plumes. Numerous models are available for the purpose (e.g., AT123D, SWIFP, Random Walk Solute Transport) which can be categorized into two groups--analytical and numerical. Analytical models estimate waste constituent concentrations and distributions using simplified, explicit expressions generated from partial differential equations. Numerical models reduce the partial differential equations to a set of algebraic equations that are solved through linear algebra using matrix techniques. Both types of models are capable of evaluating plume movement in three dimensions, but analytical models typically simplify complex physical and chemical characteristics (i.e., isotropy, homogeneity).

A comparison of the advantages, disadvantages, and examples of data obtained using the previously discussed plume delineation methods is given in Table 2. The methods used for delineating a plume at a site will probably be based upon available resources (e.g., funds, personnel, equipment), and the amount of data already available.

GROUNDWATER PUMPING

Previous utilization of pumping technologies to manage plumes has shown that these methods are most effective at sites where underlying aquifers have high intrinsic permeabilities (e.g., coarse grained sands) and where the contaminants move readily with groundwater (e.g., benzene). Pumping methods have also been utilized with some effectiveness at sites where pollutant movement is occurring along fractured or jointed bedrock. However, the fracture patterns must be traced in detail to ensure proper well placement.

Theory

The shape and size of a well's cone of depression is dependent upon the pumping rate and cycle, slope of the original water table, location of hydraulic barriers, aquifer characteristics, and location of recharge zones. Two aquifer characteristics that are important in determining the cone's configuration are the coefficients of transmissivity (T) and storage (s). Both of these parameters are inversely related to drawdown and the deepening of the cone.

The various equations used in analyzing the flow to wells under different aquifer conditions are given in Table 3. Equilibrium formulas are simpler than non-equilibrium formulas because once equilibrium conditions are reached the shape of the cone of depression does not change with time. Using these equations the effects of barrier conditions, cumulative drawdown, and discharge-recharge well interactions on the potentiometric surface can be obtained.

The equations presented in Table 3 allow the radius of influence of a well to be determined. The radius of influence is used in determining well spacing, pumping rates, pumping cycles, and screen lengths. Calculations of the radius of influence of a well can be performed exactly or approximated depending on the available data for the aquifer. Table 4 gives the various methods that can be used to calculate the radius of influence in confined and unconfined aquifers under equilibrium or non-equilibrium pumping conditions.

Two useful relationships for understanding the effects of drawdown on pumping volume and radius of influence, and for making checks on calculations are:

$$Q/H-h = 2\ K/(\ln Ro/r) = \text{constant (for confined aquifers)}$$

$$Q/H^2-h^2 = K/(\ln Ro/r) = \text{constant (for unconfined aquifers)}$$

Therefore, for a given aquifer being pumped at equilibrium, the radius of influence will not change with pumping rate. Under non-equilibrium conditions, the size of the radius of influence is determined mainly by the pumping cycle.

TABLE 2. SUMMARY OF PLUME DELINEATION METHODS

Methods	Advantages	Disadvantages	Examples of Data Obtained
Aerial image interpretation	• Can be a fairly inexpensive and rapid means of estimating plume limits	• Evidence of leachate is indirect and may be misleading	• Areas of stressed vegetations
	• Can also be used to verify site geology, hydrology, and pedology	• May provide ambiguous data	• Surface water flow patterns and other characteristics
	• Many different types of imagery exist for specialized applications	• Available imagery may not show site at an appropriate scale	• Locations of springs, faults, fracture traces, and other natural features
	• Nearly every part of the Country is covered by some type of imagery		
Hydrogeologic Investigations	• The primary method of obtaining site data needed for remedial action design and implementation	• Can be very expensive	• Aquifer characteristics (e.g., gradient, transmissivity, storage coefficient)
		• Can be fairly hazardous to investigators	• First hand evidence of wastes and leachate effects
		• Does not provide much information on plume dimensions	
Geophysical Investigations	• Fairly inexpensive and safe method of obtaining site data	• Data is sometimes ambiguous	• Areas of high/low groundwater conductivity/resistivity

TABLE 2. (Continued)

Methods	Advantages	Disadvantages	Examples of Data Obtained
Geophysical Investigations (Continued)	• Can provide data on both site geology and plume dimensions	• Techniques can be depth limited at some sites	• Locations of buried drums (metal detection, magnetometer)
	• Can provide continuous as well as discrete data		• Site geology (i.e., lithology, stratigraphy, structure)
Groundwater Sampling	• The primary method of obtaining data on plume dimensions	• Can be fairly expensive	• Concentrations of individual chemicals or chemical groups at specific locations and depths at a site
		• Can be hazardous to investigators	
		• Discrete data points are sometimes difficult to interpret	
Hydrologic Modeling	• A fairly rapid method of assessing site data in great detail	• Requires a fairly extensive amount of high quality data	• Present and future plume movement patterns
	• Can be fairly inexpensive depending upon the model chosen	• Data output must be evaluated in terms of input data accuracy and precision and assumptions	• Effects of site remediation alternatives on plume dynamics
	• A variety of computer models exist for data analysis	• Requires field and analytical verification	
		• Answers are only estimates of actual conditions.	

TABLE 3. BASIC WELL ANALYSIS EQUATIONS

Aquifer Type	Pumping Type	
	Equilibrium	Non-Equilibrium
Unconfined	$H^2 - h_w{}^2 = (Q/\pi k) \ln R_o/rw$	$H-h = (Q/4\pi T)\ W\ (\mu_A, \mu_B, \tau)$ $\mu_A - r^2\ S/4Tt$ (early drawdown) $\mu_B = r^2 Sy/4Tt$ (late drawdown) $\tau. = rK_2/H^2K_H$
Confined	$H-h_w = (Q/2\pi T) \ln R_o/r_w$	$H-h = (Q/4\pi T)\ W\ (\mu)$ $\mu = r^2 S/4Tt$

H =saturated thickness of aquifer
h_w=height of water in well
Q =pumping rate
K =coefficient of permeability (hydraulic conductivity)
R_o=radius of influence
r_w=radius of well
T =coefficient of transmissivity
$W(\mu)$ = well function
r =distance from well to drawdown measurement
S = coefficient of storage
t =time elapsed since pumping started
Sy=specific yield
K_2, K_H=vertical and horizontal permeability

TABLE 4. METHODS FOR CALCULATING RADIUS OF INFLUENCE (R_o)

Pumping Condition	Method
Equilibrium	
-Exact	$\ln R_o = \frac{K(H^2-hw^2)}{458\ Q} + \ln R_o = \frac{T(H-hw)}{229\ Q} + \ln r_w$
-Approximate	$R_o = 3(H-h_w)\ (0.47K)^{\frac{1}{2}}$
Non-Equilibrium	
-Exact	Drawdown vs. log distance plots
-Approximate	$R_o = r_w + (\frac{Tt}{4790\ S})^{\frac{1}{2}}$

R_o=radius of influence (ft)
K =permeability (gpd/ft^2)
H =total head (ft)
h_w=head in well (ft)
Q =pumping rate (gpm)
V_w=well radius (ft)
T =transmissivity (gpd/ft)
t =time (min)
S =storage coefficient (dimensionless)

Applications

Well systems can be designed to perform several functions with or without the assistance of other technologies (e.g., barrier walls). The main applications in plume management are groundwater level adjustment, plume containment, and plume removal.

Well systems to adjust groundwater levels can be designed using extraction wells to lower water levels or using injection wells to create groundwater mounds or barriers. By adjusting groundwater levels, plume development can be stopped at the source or the speed and direction of the plume can be altered. In either case contaminated water is not extracted from the groundwater system as is the case with containment and removal techniques.

Well systems used to contain a plume may incorporate extraction wells or extraction and injection wells in combination. Containment differs from removal in that the source of contamination generally is not stopped, so that contamination is an ongoing process. Because containment requires removing contaminated groundwater, a treatment or disposal method must be developed to handle the system's discharge.

Plume removal implies a complete purging of the groundwater system to remove contaminants. Removal techniques are suitable when contaminant sources have been stopped (e.g., by waste removal or site capping) or contained (e.g., by barrier walls) and aquifer restoration is desired. Extraction or extraction and injection well systems can be used in plume removal. Numerous arrays and patterns are available for injection/extraction wells and the choice is usually made based on suitability for a specific job. Extraction/injection techniques can also be used with flushing compounds to accelerate contaminant removal. As with containment designs, treatment of pumped water is necessary.

Well Design and Installation

Selecting and designing the appropriate well system requires that adequate information be available on the site's hydrogeologic conditions and the plume's characteristics. Four basic types of wells are used in plume management: well points; suction wells; ejection wells; and deep wells. Using the site data, selection of an appropriate well type can be made. Table 5 lists selection criteria for these well types.

The installation of wells varies with geologic materials, well type, and diameter, but most installations consist of opening the well hole, installing casing, completing the well, and developing the well. The first of these steps consists of dislodging and removing the earth materials located in the path of the well. Screens and casings may be installed simultaneously with the opening of the hole or after the hole has been completed. The sequence of events depends upon the technique used to open the hole and the geologic characteristics in the immediate vicinity of the hole. Installation of screens, filters, pumps, and grout completes the construction of the well. Well development is the last step and consists of removing material that has built up on the well screen and walls of the borehole during the previous steps. Removal of these particles maximizes well yield and prevents pump damage. Table 6 gives various installation methods used for wells, and method restrictions.

SUBSURFACE DRAINS

Subsurface drains include any type of buried conduit used to collect liquid discharges (i.e., contaminated groundwater) by gravity flow. The major components of a subsurface drainage system include: drain pipe(s), envelope and/or filter, backfill, manholes or wetwells, and pumping station(s).

TABLE 5. CRITERIA FOR WELL SELECTION (adapted from Reference 12)

Parameters	Wellpoints	Suction Wells	Ejector Wells	Deep Wells
Hydrology				
o Low permeability (e.g., silty or clayey sands)	Good	Poor	Good	Fair to Poor
o High permeability (e.g., clean sands and gravel)	Good	Good	Poor	Good
o Heterogeneous materials (e.g., stratified soils)	Good	Poor	Good	Fair to Poor
o Proximate recharge	Good	Poor	Good to Fair	Poor
o Remote recharge	Good	Good	Good	Good
Depth of Well	Shallow < 20 ft	Shallow < 20 ft	Deep > 20 ft	Deep > 20 ft
Normal spacing	5-10 ft	20-40 ft	10-20 ft	> 50 ft
Normal range of capacity (per unit)	0.1-25.0 gpm	50-400 gpm	0.1-40.0 gpm	25-3000 gpm
Efficiency	Good	Good	Poor	Fair

TABLE 6. METHODS OF WELL INSTALLATION

Method		Applications			Casing/Screen Installation	Comments
Basic	Variations	Geologic Material	Maximum Well Dia. (in)	Maximum Well Depth (ft)		
Hand	Augers	Soft, without excess sand and water, no boulders	6	20	Driven after opened	
	Driving points	Soft soil free of boulders	3	30	Driven as hole proceeds	Wider and deeper can be machine driven
Boring	Rotary Auger bucket	Soft soils without excess boulders	48	90	Driven after hole opened	Typically limited to 24-in. diameter wells or less
	Spiral Auger	Soft soil without excess sand and water, no boulders	6	90	Driven after hole opened	Cannot be used below water table, must be used in combination with other techniques
Jetting	Self Jetting	Soft soils free of boulders	8	50	Driven as hole opened	Jetted wells require less development
	Wellpoint/ Riser Unit	Soft soils free of boulders	8	50	Driven as hole opened	Method uses large quantities of water
	Separate temporary jetting pipe	Soft soils free of boulders	8	100	Placed after hole opened	

TABLE 6. (Continued)

Method		Applications			Casing/Screen Treatment	Comments
Basic	Variations	Geologic Material	Maximum Well Dia. (in)	Maximum Well Depth (ft)		
Jetting (Continued)	Separate Permanent jetting pipe	Soft soils free of boulders	8	100	Driven as hole opened	
	Jet Percussion	Soft soils free of boulders	24	200	Placed after hole opened	
	Rotary hole puncher	Soft soil, sand stone, schist	24	200	Placed after hole opened	
Rotary Drilling	Conventional hydraulic	Any type	-	-	Placed after hole opened	Typically used for deep wells, quickest drilling method
	Reverse flow	Any type, boulders may be a problem	60	-	Placed after hole opened	Require large quantities of water
	Air Rotary	Any type	12	-	Placed after hole opened	Very fast method
	Air rotary with pneumatic hammer	Any type	8	-	Placed after hole opened	

Theory and Applications

Subsurface drains function similarly to an infinite line of extraction wells. That is, they effect a continuous zone of depression which runs the length of the drainage trench.

Functionally, there are two basic types of drains--relief drains and interceptor drains. Relief drains are installed in areas where the hydraulic gradient is relatively flat. They are generally used to lower the water table beneath a site or to prevent contamination from reaching a deeper, underlying aquifer. Relief drains are installed in parallel on either side of the site such that their areas of influence overlap and contaminated groundwater does not flow between the drain lines. They can also be installed completely around the perimeter of the site.

Interceptor drains, on the other hand, are used to collect groundwater from an upgradient source in order to prevent leachate from reaching wells and/or surface water located hydraulically downgradient from the site. They are installed perpendicular to groundwater flow. A single interceptor located at the toe of the landfill, or two or more parallel interceptors may be needed, depending upon the circumstances.

Whether a drain functions like an interceptor or a relief drain is determined by the hydraulic gradient. The design of these two drain types differs but construction and installation are the same.

Although subsurface drains perform many of the same functions as pumping systems, drains may be more cost effective under some circumstances. For example, they may be particularly well suited to relatively low permeability sites where the cost of pumping may be prohibitively high because of the need to space wells very close together.

There are, however, a number of limitations to the use of subsurface drains as a remedial technique. They are not well suited to areas of high permeability and high flow rate. Also, contamination at great depth may cause construction costs to be prohibitive, particularly if a substantial amount of hard rock must be excavated. Subsurface drains are also not suitable when the plume is viscous or reactive, since this type of leachate may clog the drain system.

Design

When a drainage system is being designed the following elements must be specified:

- Drain type
- Drain depth
- Spacing, if parallel drains are required
- Drain diameter and gradient (hydraulic design).

Drainage systems are classified by function (i.e., as either relief or interceptor drains), by the type of drain pipe, and by their configuration. Perforated pipe, available in chemically resistant concrete, vitrified clay, and various plastics, is the most widely used drain pipe for remedial action work, particularly if the drains are to be placed deep in the substratum. Other types of drainage conduits include jointed clay and concrete tiles and flexible corrugated plastic pipe.

The configuration of the drainage system depends on the site configuration and size, and the flow rate. The system may be singular, consisting only of lateral pipes discharging to a collection sump, or composite where laterals discharge to larger collector pipes which may in turn discharge into a main before reaching a collection sump.

In a subsurface drainage system containing parallel relief drains, depth and spacing are interdependent design variables. In theory, the deeper the drains are the greater the spacing that can be used to obtain the same zone of depression. This relationship between depth and spacing is critical to the design of effective parallel drainage systems. In designing a system for hazardous waste sites, it must be determined whether the drawdown curves of parallel drains located on either side of the site will intersect and thereby capture the entire plume. It may be necessary to manipulate depth and spacing in order to capture the entire plume. However, in designing parallel drains for hazardous waste sites, a minimum spacing is often imposed by the boundaries of the waste since excavation through the waste material can be extremely hazardous. A maxiumum depth may be imposed by the prohibitive cost of trench excavation.

Numerous equations, models, and analogues have been developed for determining appropriate spacing of parallel relief drains under various idealized conditions. Donnan (5) developed a formula for determining drain spacing for drainage systems which extend to the depth of an impermeable barrier (Table 7-A). It is evident from this formula that spacing is a function not only of drain depth, but also of the hydraulic conductivity and flow rate. In many instances, relief drains will not be installed to the full depth of an impermeable barrier due to high costs. Under these circumstances, design equations must account for radial flow to the drain from the underlying permeable layers as well (Table 7-B). Hooghoudt's formula (9) was developed to account for this radial flow. A number of nomographs are available to aid in solving Hooghoudt's equation.

Design of interceptor drains is different from that of relief drains. In order to decide where to position the drain to intercept the desired flow, the relationship between depth and flow, and the upgradient and downgradient influence of the drain must be known.

The shape of the drawdown curve upgradient of the site is independent of hydraulic conductivity but is a function of head or hydraulic gradient. The upgradient influence or drawdown extends for a distance which is inversely proportional to the water table gradient. The distance to which the water table is lowered downgradient of the interceptor drain is directly proportional to the depth of the drain. Theoretically, a true interceptor drain lowers the water table downgradient to a depth equal to the depth of the drain. The distance downgradient to which it is effective in lowering the water table is infinite provided there is no recharge. This however is never the case since infiltration from precipitation recharges the groundwater. The quantity of flow is also proportional to the depth of the drain. If an interceptor drain is placed at the midpoint between the water table and an impervious layer, a little less than 50 percent of the flow will be intercepted. The upgradient and downgradient influence of an interceptor drain and the quantity of flow intercepted can be determined theoretically or in the field.

The upgradient influence can be determined from the equation

$$D_u = 4/3\ H \tan \alpha$$

where

D_u = effective distance of drawdown upgradient

H = saturated thickness of the water bearing strata not affected by drainage

$\tan \alpha$ = angle between the initial water table or ground surface and the horizontal plane.

The theoretical expression for the downgradient influence is

$$D_d = \frac{K \tan \alpha}{q} (h_1 - h_2 + D_2)$$

where

K = hydraulic conductivity

q = drainage coefficient

h_1 = effective depth of the drain

h_2 = desired depth to the water table after drainage

TABLE 7. STEADY STATE DRAIN SPACING FORMULA FOR PARALLEL RELIEF DRAINS

Situation	Formula	Description
(A) Flow to drains resting on an impermeable barrier (5).	$Q = \frac{4\ K(H^2 - D^2)}{L^2}$ or when D << H, $Q = \frac{4Kh^2}{L^2}$	Q = discharge rate per unit surface area (m/day) K = hydraulic conductivity (m/day) H = height of the water table above the impervious floor (m) D = Thickness of the aquifer below drain level (m) L = drain spacing (m) h = height of water table above drain level, midway between 2 drains (m)
(B) Flow to drains at the interface of two permeable layers (9).	Presuming D << H $Q = \frac{8K_2dh + 4K_1h^2}{L^2}$	d = thickness of the "equivalent layer" or area of radial flow (m)

D_1 = distance from the ground surface to the water table at the drain

D_2 = distance from the ground surface to the water table before drainage at the distance D_d downgradient from the drain

D_d = distance downgradient from the drain where the water table is lowered to the desired depth.

In the equation given above, D_d and D_2 are interdependent variables. In obtaining the solution to the equation, it is necessary to estimate the value of D_2 and then make a trial computation. If the actual value of D_2 at distance D_d is appreciably different, a second calculation is necessary. Where $\tan \alpha$ is uniform throughout the area, D_2 can be considered equal to D_1. D_d is the distance downgradient from the drain to which the water table is lowered to the depth required to capture the plume. If a second interceptor is needed, it would be located the distance D_d downgradient from the first (16).

In addition to designing the subsurface drainage system for appropriate depth and spacing, the hydraulic design must also be developed. The drain's pipe size and gradient must be adequate to carry away the water after it enters the pipe. The gradient of the drain pipes should be great enough to result in a flow velocity that prevents siltation yet will not cause turbulence. SCS has published data on minimum recommended grades for various pipe diameters and maximum velocities recommended for various soil types (16). The diameter of the drain for a given capacity is dependent on flow, hydraulic gradient, and the roughness coefficient, n, which is a function of the hydraulic resistance of the drain material. The formula for hydraulic design is based on the Manning formula for rough pipes which is written as follows:

$$Q = av = (1/n)(R^{2/3})(i^{1/2})$$

in which

Q = discharge

R = hydraulic radius (equal to the wet cross-sectional area, a, divided by the wet perimeter)

i = hydraulic gradient

1/n = roughness coefficient

v = velocity

a = area

SCS(16) and Cavelaars(3) have developed nomographs for estimating pipe diameter based on the Manning formula when hydraulic gradient, flow rate, and drainage area are known. Roughness coefficients have been published for all drain types.

The other criterion for successful hydraulic design is to ensure that the pipe will accept the drainage water when it arrives at the drainline. To meet this criterion, the relationship between the hydraulic conductivity of the gravel envelope and/or filter material, the perforations in the drain pipe, and the hydraulic conductivity of the base soil material must be evaluated. The primary function of a filter is to prevent soil particles from entering and clogging the drain. The function of an envelope is to improve water flow into the drains by providing a material that is more permeable than the surrounding soil. Although filters and envelopes have distinctly different functions, it is possible to meet the requirements of both a filter and an envelope. SCS(16) has developed distinct design criteria for gravel filters and envelopes whereas the Bureau of Reclamation (2) has developed one set of standards for a well-graded envelope which meets the requirements of both a filter and an envelope. For tile drains the criteria are based upon a comparison of the grain sizes of the envelope and base soil material. Where perforated pipe drains are being used, the minimum size of the envelope material is based on the size of the perforations. Geotextile fabrics offer an alternative to the more conventional sand and gravel filters provided the fabrics are compatible with the waste components in the leachate so that the drains do not clog.

Design of the drainage sump and pumping plant are also considered part of the total hydraulic design. The main steps in their design include:

- Determining the maximum inflow to the sump
- Determining the amount of storage required
- Calculating the pumping rate
- Determining the start, stop, and discharge levels
- Determining the type and size of the storage tank
- Selecting the pump and the motor.

Construction and Installation

Construction and installation of subsurface drains can be divided into two major phases--trench excavation and drain installation. Trench excavation is often the most complex and costly aspect of construction and installation. The ease or difficulty of excavation can have a dramatic effect on the cost of the total installation. A difficult excavation may result in exclusion of subsurface drainage as a viable technique because of prohibitive costs. Table 8 summarizes the various activities involved in trench excavation, equipment or methods suitable for carrying out these activities, and the major application(s) and limitation(s) of these methods. Many of these methods are also used in construction of barrier walls, discussed in the next section. Once trench excavation is completed the components of the subsurface drain can be installed. This process consists of installing drain pipe bedding, drainage pipe, a gravel or soil envelope, filter fabric, backfill, and auxiliary components including manholes and pumping stations.

BARRIER WALLS

Low permeability barriers can be used to divert groundwater flow away from a waste disposal site or to contain contaminated groundwater leaking from a waste site. There are three major types of low permeability barriers that are applicable to leachate plume management--slurry walls, diaphragm walls, and grout curtains (10, 17).

A slurry wall is a subsurface barrier that is formed through the excavation of a trench using a bentonite and water slurry to support the sides. The trench is then backfilled with materials having far lower permeability than the surrounding soils. The slurry backfill trench or slurry wall reduces or redirects the flow of groundwater.

A diaphragm wall is a subsurface barrier designed for structural strength and integrity in addition to low permeability. Diaphragm walls can be made of cast-in-place concrete or precast panels with cast-in-place joints.

A grout curtain is a subsurface barrier formed through the pressure injection of one of a variety of special grouts, into a rock or soil body to seal and strengthen it. Once in place, these grouts set or gel into the rock or soil voids, greatly reducing the permeability of and imparting increased mechanical strength to the grouted mass. As this process is carried out, a grout wall or curtain results. Because a grout curtain can be three times as costly as a slurry wall, it is rarely used when groundwater has to be controlled in soil or loose overburden. Grout is used primarily to seal voids in porous or fractured rock when other methods of controlling groundwater are impractical.

Design

Barrier walls are classified by the materials of which they are composed and the position in which they are placed with respect to the pollution source. There are three major types of barrier walls that are categorized according to the material that is used to backfill the trench:

- Soil-bentonite
- Cement-bentonite
- Diaphragms.

Soil-bentonite walls are composed of soil materials (often the trench spoils) mixed with small amounts of the bentonite slurry from the trench. Cement-bentonite walls are composed of a slurry of portland cement and bentonite. Diaphragm walls are

TABLE 8. METHODS AND EQUIPMENT APPLICABLE FOR TRENCH EXCAVATION (4, 12, 14)

Activity	Method/Equipment	Applications/Limitations
Subsurface Exploration	Direct excavation (using backhoe and ripper)	Applicable under most circumstances.
	Drilling	Usually carried out to determine extent of groundwater and soil contamination. This data may be applicable if appropriate drilling logs are kept.
	Seismic testing	
	sledge hammer-disk	Suitable for limited explorations - distances to 300 feet and depths up to 100 feet.
	blasting	Not recommended for hazardous waste sites; may result in rock fracturing, which can cause movement of the plume to an underlying aquifer. May result in secondary detonation of explosives or air pollution.
Rock Fragmentation	Mechanical ripping	Use is limited to trench depth of about 6 feet or less, unless the ripper can be lowered into the trench to reach greater depths.
	Impact methods	Low production rate generally limits usage to a small scale.
	Blasting	(see comment above)
	Non-explosive demolition	Alleviates environmental problems associated with blasting, but the process is expensive and time consuming.

TABLE 8. (Continued)

Activity	Method/Equipment	Applications/Limitations
Excavation	Trenchers	Can provide continuous excavation, but is only suitable in soil or well fragmented rock. Maximum depth for a large wheel trencher is 8.5 feet; 27 feet for bucket ladder type trencher.
	Backhoe	Excavate to depths of up to 70 feet; can excavate rock up to one-half the bucket diameter; diameters up to 4 yd^3 are available. Large size may preclude use in urban areas
	Clamshell and draglines	Used when the trench depth is below the limit of other equipment. Limited to loose rock and earth.
Wall Stabilization Methods	Shoring	Most widely used stabilization method. Method varies with the depth of the trench.
	Ground freezing	Expensive; may require very low temperature to freeze clay.
	Open cuts	Limited to very shallow trenches
Dewatering	Open pumping	Applicable to shallow trenches with stable soils of low permeability. May require treatment of contaminated groundwater; Inexpensive
	Predrainage using well points or wells	Applicable under most circumstances but depth of trench and soil permeability may make this method cost prohibitive
	Groundwater cutoff	Often used together with open pumping to prevent low rates of seepage

TABLE 8. (Continued)

Activity	Method/Equipment	Applications/Limitations
Grade Control	Visual method (target grade control)	Precision and accuracy depend on machine operators skills and alertness
	Automatic method (laser beam)	Trenches and backhoes can be equipped with this system; high accuracy and precision

composed of pre-cast or cast-in-place reinforced concrete panels (diaphragms) installed by excavating a short, slurry-supported trench section, using a clamshell bucket or other suitable piece of equipment. Upon completion of excavation, the trench section is filled with a pre-cast, reinforced concrete panel or tremied concrete around a reinforcement cage. Alternate or primary panels are installed first followed by the secondary panels. Joints between panels are formed using stop end tubes that are concreted after adjacent panels are completed. Another method involves using a cement-bentonite slurry as the excavation fluid which forms the joint between panels when set.

In general, soil-bentonite walls can be expected to have the lowest permeability, the widest range of waste compatibilities, and the lowest cost. They also offer the least structural strength (highest elasticity), usually require the largest work area, and are restricted to a relatively flat topography unless the site can be terraced.

Cement-bentonite walls can be installed at sites where there is insufficient work area to mix and place soil-bentonite backfill. By allowing wall sections to harden and then continuing the wall at a higher or lower elevation, they can be installed in a more extreme topography. Although cement-bentonite walls are stronger than soil-bentonite walls, they are at least an order of magnitude more permeable, resistant to fewer chemicals, and more costly.

Diaphragm walls are the strongest of the three types as well as the most costly. Provided the joints between panels are installed correctly, diaphragm walls have approximately the same permeability as cement-bentonite walls and, because of a similarity of materials, about the same chemical compatibilities. Diaphragm walls are most typically used in situations requiring structural stength and relatively low permeability.

Combinations of these three major backfill types may be included within the same wall. For example, a soil-bentonite backfill may be used for the majority of a wall with cement-bentonite backfill being used in areas that require greater strength, such as a road or rail crossing. Being able to combine the various types of walls makes this technique adaptable to a wider range of site characteristics.

The vertical and horizontal positioning of a barrier wall with respect to the location of the pollution source and groundwater flow characteristics is known as configuration. There are two types of configurations--vertical and horizontal. The wall configuration, combined with any other remedial measures (e.g., pumping, capping), determine how effective a barrier wall will be in controlling leachate plume migration.

Vertical configuration refers to the depth of the wall with respect to both geologic formations and the water table. Based on vertical positioning, walls are either "keyed" into a low permeability formation below the aquifer, or placed to intercept only the upper portion of the aquifer. The latter type, known as a "hanging" barrier wall, can be used to control contaminants, such as petroleum products, which do not mix with the groundwater but float on top of it. In these situations, the barrier need only extend to a depth in the water table sufficient to intercept the contaminants. Keyed-in barrier walls are excavated through the water table to a confining layer below it to contain contaminants that mix with or sink to the bottom of the aquifer. The connection between the wall and the low permeability zone is very important to the overall effectiveness of the barrier.

Horizontal configuration refers to the positioning of the barrier relative to the location of the pollution to be controlled and the direction of groundwater flow (i.e., the gradient). Based on horizontal configuration, barrier walls may completely surround the pollution source or be placed upgradient or downgradient from it.

Circumferential placement refers to placing a barrier wall completely surrounding the site. Although this requires a greater wall length and higher cost than either upgradient or downgradient placement alone, it does offer some advantages and is a common practice. A circumferential barrier wall, when used with a surface infiltration barrier such as a cap, can greatly reduce the amount of leachate a site will release to the environment. If a leachate pumping or drainage system is used, as often is the case, a waste site can be virtually dewatered. In addition to vastly reducing the amount of leachate to be treated, dewatering can help increase the longevity of the wall.

Upgradient wall placement refers to the positioning of a wall on the groundwater source side of a waste site. This type of placement can be used where there is a relatively steep gradient across the site in order to divert uncontaminated groundwater around the wastes. In such cases, clean groundwater is prevented from becoming contaminated thereby reducing leachate treatment requirements.

Placement of a barrier wall on the side opposite the groundwater source is referred to as downgradient placement. This placement configuration does nothing to limit the amount of leachate being generated and so is practical only in situations where there is a limited amount of groundwater or contaminant flow such as near drainage divides. This type of barrier can contain leachate so it can be recovered for treatment. Although this wall configuration may be keyed-in for miscible or sinking contaminants, it is most often hung to contain and recover floating contaminants.

The effectiveness of barrier walls can be dramatically increased by incorporating additional remedial measures into the overall plan addressing the problem. A barrier wall combined with a groundwater pumping system, for example, can be used to trap contaminated groundwater and then pump it to a treatment system. Additionally, surface drains can prevent water from infiltrating into a waste disposal area while the barrier wall reduces groundwater flow into the site. Other remedial measures which may be used in conjunction with barrier walls include surface sealing, sheet piling, synthetic membrane installation, and grouting.

Grouting materials fall into three basic groups--cement, bituminous, and chemical. Some specific grout mixtures include portland cement, sand-cement, clay-cement, clay-bentonite, bituminous emulsions, sodium silicate, and acrylamide. The applicability of each material is based on the size of the openings in the soil or rock formation, and the anticipated area of grout penetration. The major grouts in use are cement and clay which make up approximately 95 percent of all grouts used.

Cement grouts utilize materials that set, harden, and do not disintegrate in water. Because of their large particle size, cement grouts are more suitable for rock than for soil applications. Materials may be added to cement grouts to improve their applicability. Sand may be added to portland cement to create a grout suitable for coarse materials, while bentonite may be added to improve the penetration of cement in alluvial soils.

Clays have been used widely as grouts either alone or in formulations. In general, coarse sands and gravels are initially grouted using clay or clay-cement because they are inexpensive. Bentonite is an excellent clay grouting material because of its swelling and gel formation properties (1).

Grout curtains are the most practical and efficient method for sealing fissures, solution channels, and other voids in rock. There are four basic techniques for installing a grout curtain. These are:

- Stage-up method
- Stage-down method
- Grout-port method
- Vibrating beam method (8).

The first three methods are injection methods in which the grout is injected from either the bottom of a borehole to the top (stage-up), or the top of a borehole to the bottom (stage-down), or through a slotted injection pipe that has been sealed into the borehole with a brittle portland cement/clay mortar jacket (grout-port). The grout port method utilizes rubber sleeves which cover the outside of each slit (or port) permitting grout to flow only out of the pipe (8). The vibrating beam method is not an injection technique, rather, it is a way of placing the grout in which an I-beam is vibrated into the soil to the desired depth and then raised at a controlled rate. As the beam is raised, grout is pumped through a set of nozzles mounted on the base of the beam, thus filling the newly formed cavity. When the cavity is completely filled, the beam is moved in the direction of the wall, leaving a suitable overlap to ensure continuity. The process is continued until a wall of the desired length is constructed (7).

As with slurry walls, placing a grout curtain upgradient from a waste site can redirect flow so that groundwater no longer contacts the wastes that are creating the leachate plume. However, placement of a grout curtain downgradient from a hazardous waste site may not be successful because of grout/leachate interactions. For example, in many instances it would be difficult to control the grout setting time, and thus, be difficult to emplace a curtain of reliable integrity. Additional problems can occur in attempting to grout a horizontal curtain or layer beneath a waste site in that injection holes must be drilled either directionally from the site perimeter, or directly through the wastes (10). The first case may not always be feasible and may be quite costly and the second might be quite hazardous to construction crews.

IN-SITU TECHNIQUES

Leachate plumes may be treated in-place by certain biological and chemical treatment methods that are specifically designed to remove plume contaminants. Contaminant plumes consisting chiefly of biodegradable organics may be treated by in-place biodegradation, or bioreclamation. Chemicals may also be injected into the leachate plume to neutralize, stabilize, or mobilize contaminant materials. For example, soil flushing is used as an in-situ technique to flush residual contaminants from soil particles in order to mobilize them for collection and treatment. Usually water is used as the flushing media, however, the use of dilute solutions of surfactants and organic solvents has also been proposed.

Bioreclamation

Bioreclamation is an in-situ groundwater treatment technique based on the concept of utilizing microorganisms, combined with aeration and the addition of nutrients, to accelerate the biodegradation rate of groundwater contaminants.

Many species of bacteria, actinomycetes, and fungi have been found to degrade hydrocarbons associated with petroleum. Bacteria are the prime microorganisms involved with biodegradation of organics in groundwater. Naturally occurring species of the genera Pseudomonas, Arthrobacter, Nocardia Achromobacterium, and Flavobacterium have been found to attack petroleum hydrocarbons and other organic chemicals (13). These bacteria can be stimulated by adding nutrients and oxygen to develop a population that is adapted to readily degrade organic chemicals present in groundwater.

An alternative to developing adapted populations from naturally occurring bacteria is to inoculate the subsurface with mutant microorganisms developed in the laboratory to degrade specific organic chemicals or chemical groups. The particular advantages of this alternative is that overall biodegradation rates of specific organics may be increased and the time required for adaptation of a naturally occurring population is eliminated. In this method, the parent microorganisms are collected from a naturally occurring source containing the specific chemical groupings, such as oil refinery treatment plant sludge for phenol and cyanide treatment. Mutant strains are developed from irradiation and these mutant bacteria are cultured in large amounts and packaged for use. The mutant bacteria can be cultured in even larger amounts in holding ponds at the site and introduced into the subsurface by spray irrigation, surface flooding, or subsurface injection.

As mentioned earlier, nutrients and oxygen are required for proper cell growth and respiration. Cell nutrients include nitrogen, phosphorus, and trace elements (i.e., potassium, sulfur, sodium, calcium, magnesium, iron, and copper). Groundwater usually contains sufficient amounts of nitrogen and phosphorous for degradation of only 10 to 20 milligrams per liter (mg/l) of organic material. More nutrients must be added for biodegradation of higher contaminant levels. Oxygen is also required for the aerobic decomposition of organics by bacteria. Roughly 3 or 4 mg/l of oxygen are required for every milligram per liter of organic constituent degraded (15). A constant supply of dissolved oxygen must be supplied to the contaminated groundwater. Subsurface aeration has been the method most commonly used during previous bioreclamation of groundwaters contaminated with gasoline. However, since this method can only provide a maximum of about 10 mg/l of dissolved oxygen, biodegradation of high levels of organics in the subsurface can be limited. Alternative oxygenation techniques include the use of pure oxygen systems, ozone, and low levels of hydrogen peroxide.

The selection of bioreclamation as a plume management technique depends on the biodegradability of the components in the contaminant plume. Biodegradabilities of various organic substances are based on the ratio of Biochemical Oxygen Demand (BOD) to Chemical Oxygen Demand (COD). Compounds with a BOD/COD ratio of less than 0.01 are considered relatively undegradable, compounds with a ratio of 0.01 to 0.1 are considered moderately degradable, and compounds with a ratio of 0.1 or greater are considered degradable (11).

Implementation of the bioreclamation process involves the placement of extraction wells to control migration of the contaminant plume by pumping. Groundwater pumped to the surface is mixed with nutrients and reinjected upgradient of the extraction wells. Specialized mutant bacteria may also be added along with the nutrients. The groundwater may be oxygenated via air, oxygen, or hydrogen peroxide.

The bioreclamation technique has been used successfully in a number of cases to treat contaminated groundwater plumes from underground gasoline and hydrocarbon leaks. It has not yet been demonstrated for groundwater treatment at uncontrolled hazardous waste disposal sites. However, its potential to treat hydrocarbon contaminated groundwater establishes it as a viable technique.

In-Situ Chemical Treatment

In-situ chemical treatment techniques involve the injection of a chemical into a leachate plume to neutralize, detoxify, precipitate, or othewise affect the contaminant materials. These techniques are highly dependent on the contaminant and have in the past been used only for spills of specific chemicals. Dilute solutions of acids or bases, such as nitric acid or sodium hydroxide, could theoretically be used to neutralize acidic or basic groundwater contaminants. A system of extraction/injection wells could be used to disperse the neutralizing agent, and contain and cycle groundwater until the appropriate pH was attained. Similarly, chemical agents could be used in this manner to detoxify plume contaminants. Sodium hypochlorite, for instance, has been used to oxidize cyanide-contaminated groundwaters. Other oxidizing chemicals such as hydrogen peroxide or ozone may find potential application in this type of remedial approach. Solutions of sodium sulfide have also been proposed to precipitate toxic metals from groundwater, thereby resulting in their immobilization. Recently, an underground spill of acrylate monomer was attenuated by the injection of a catalyst which caused the plume of acrylate monomer to polymerize and solidify (18).

The above methods, although primarily applicable to spills of a single substance, may find some use for controlling contaminant plumes from hazardous waste sites.

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THE INFLUENCE OF SELECTED ORGANIC LIQUIDS ON THE PERMEABILITY OF CLAY LINERS

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ABSTRACT

Research on the influence of organic chemicals on permeability of clay soils used to line waste impoundments has continued. Three types of simulated clay liners have been prepared by mixing selected clay minerals with sandy loam soil to achieve permeabilities to water normally considered acceptable for waste impoundments. These liners were subjected to two hazardous wastes, a xylene paint solvent waste and a contaminated acetone waste, in both laboratory permeameters and field cells. Wastes were tagged with tracer dyes to facilitate visual and microscopic observation of their movement through soil. Laboratory studies were directed at determining the influence of different initial moisture contents and elevated pressures on the permeabilities of clay liners subjected to these wastes. Both the initial moisture content and elevated pressures influenced the time required for permeability changes to occur. The pressures at which the soils were tested did not influence the final permeabilities attained. Samples tested at compaction moisture typically attained final permeabilities one to two orders of magnitude greater than those attained on samples presaturated with water.

The field study is still in progress, but the preliminary data corresponds closely to the laboratory predictions of increased permeability. Visual observations of dye paths and chemical analyses of small soil samples from both laboratory and field studies indicated that the wastes moved through preferential channels in the center of the soil mass and not along the edges of the permeameters or test cells.

INTRODUCTION

Compacted clay soils have long been used to line waste storage and disposal facilities including waste piles, surface impoundments, and landfills. Design specifications have in the past been developed using only water as the permeant liquid. Such installations have generally been successful when the primary liquid to be retained was relatively pure water.

It has long been known that smectite clay subjected to some organic chemicals exhibited smaller spacing between adjacent crystalline layers than when exposed to water (Barshad, 1952). Only recently, however, have measurements been made of the impact of organic liquids on permeability of recompacted clay soils. Previous reports by Anderson et al. (1982) and Brown and Anderson (1983) evaluating the impact of concentrated organic liquids on the permeability of four native clay soils indicated that the permeabilities may be 2 to 3 orders of magnitude greater than those measured with water. Observations of the permeated soil cores indicated physical changes in the soil structure.

The present studies were conducted with three clay soils compacted in fixed wall permeameters. Liquids were passed through the soils under elevated hydraulic gradients (61.1 and 361.6) to shorten the testing time. Although laboratory determined permeabilities have been traditionally used to estimate field permeability of such soils, it was believed necessary to collect data using wastes under conditions as similar as possible to those anticipated in a field installation of clay soils compacted to serve as a landfill liner. Thus, a field study using three soils of different clay mineralogies permeated by two organic solvent wastes was undertaken to further evaluate the validity of the laboratory testing procedure and to provide field data on the impact of organic liquid wastes on the permeability of clay liners.

MATERIALS AND METHODS

Soil

Each of the three clay soils were blended with a predetermined amount of sandy loam soil to attain permeabilities in the range of 1 x 10^{-7} to 1 x 10^{-8} cm/sec. These three clay soils were selected to represent the range of materials most widely available and used for constructing waste impoundment liners. In all following discussion, the clay soil blends will be referred to by their dominant mineralogies of kaolinite, mica, and bentonite. The textures and mineralogies of the clay soil blends are given in Table 1. The chemical properties are given in Table 2. Exchangeable cations in the kaolinitic and micaceous clay soils were predominantly calcium, while the bentonitic clay soil was sodium saturated.

Wastes

The wastes were selected to be representative of polar and nonpolar organic chemical wastes usually generated in large quantities. The xylene waste was a paint solvent used to clean factory paint sprayer lines and contained 20% by volume solids. The solids were predominantly paint pigments composed of Fe, Cr, Ti, Cu, K, S, P, Si, and Al. The waste was allowed to settle in drums for 4 months prior to use. The liquid following settlement, still containing 25% by weight plasticizers and suspended pigments, was decanted for use in the test cells. A representative sample of the waste was distilled, and an infrared analysis confirmed that the liquid was xylene with only trace amounts of water present. The acetone waste was a chemical manufacturing waste consisting of of 91.7% acetone, 4% benzene, 0.6% phenol, and 3.7% unknown (percent by weight). Two dyes were added to each waste to facilitate visual observations of their movement. In both wastes, the dyes used were Automate Red B and Fluorescent Yellow at 154 and 50 mg/l, respectively.

Table 1. Physical Properties of the Three Clay Soils Blended for Use.

Clay	USDA Textural Class.	Particle Size Distribution Sand	Silt	Clay	Mineralogy	Organic Carbon (%)	pH (1:1 Soil:H_2O)
		----------------	(%)	-----------			
Kaolinite	SCL[+]	62.8	13.6	24.5	K-1[++]M-tr	0.53	7.7
Mica	SCL	60.4	17.6	22.0	Mi-1 K-2 M-3	0.17	8.0
Bentonite	SCL	75.9	3.9	20.2	B-1 Mi-tr	0.29	8.9

+ SCL = sandy clay loam
++ K = kaolinite*
Mi = mica*
B = bentonite*
M = montmorillonite
1 = dominant mineralogy
2 = 2nd most dominant mineralogy
3 = 3rd most dominant mineralogy
tr = trace quantity

* = commerically obtained

Laboratory Testing Procedure

Soils were compacted in fixed wall permeameters as described in previous reports by Anderson *et al.* (1982) and Brown and Anderson (1983). Compaction was to at least 90% Proctor density; hydraulic conductivity measurements were conducted with soils slightly wet of optimum. Permeability tests with water (0.01 N $CaSO_4$) were conducted on replicate samples. The effects of pressure on permeability were tested with both wastes on laboratory compacted soils which had been saturated first with 0.01 N $CaSO_4$ and on unsaturated soils at the moisture content used for compaction. Pressures of 5, 15, and 30 psi equivalent to hydraulic heads of 31, 91, and 181 were tested. Samples tested with water were permeated until approximately 1 pore volume of water had penetrated the core. The liquid chamber was then opened, waste was substituted for the water, and pressure was reapplied. Samples of effluent were collected, quantified, and subsampled for analysis. Collection continued until the permeability data indicated no further increase or until the flow exceeded the reliable range of the measurements.

Morphology

Samples of the compacted clay soils permeated with water and the two wastes were collected from both laboratory and field studies for morphological evaluations. The cores were vacuum impregnated with an epoxy resin and sliced into thin sections for petrographic and epifluorescent microscopy. A line-point traverse method (Brewer, 1976) was used to determine porosity and pore size distribution. Information on the size and the fraction of pores stained by the dyes is currently being gathered in an effort to identify the pathways by which the fluids have penetrated the soils.

Field Procedures

Field cells were constructed and lined on all four sides and bottom with 100-mils high-density polyethylene (HDPE) liners to facilitate leachate collection and eventual removal of the clay soil liners for dissection and observation. The clays soils were compacted, and a head of waste was placed on the liners. Leachate was collected periodically for use in calculating permeability according to Darcy's

Table 2. Chemical Properties of Three Blended Clay Soils.

Clay	CEC meq/100 g soil (NaOAc)	CEC meq/100 g clay (NaOAc)	ESP	SAR	NH_4OAc Extractable			
					Ca	Mg	Na	K
					meq/l			
Kaolinite	9.4	38.0	3.0	1.3	26.0	2.1	0.5	0.3
Mica	7.3	33.0	5.0	3.0	20.5	2.8	0.9	0.2
Bentonite	18.9	94.0	84.0	84.7	29.7	3.2	20.5	0.2

Law. A schematic diagram of the cells is shown in Figure 1.

The 28 field cells (1.5 m x 1.5 m x 1.8 m inside dimensions) were constructed of reinforced concrete. A wooden platform (1.5 x 1.5 m x 0.15 m) with lifting devices on each corner was placed in each cell to facilitate final removal of the clay liners. HDPE liners 0.25 cm thick were installed in each cell and extended to the top of the cell walls. A collection system consisting of a manifold of four 0.95 cm inside diameter perforated copper tubes was laid on the HDPE liner and covered with 5 cm of washed masonry sand.

The optimum water content for field compaction, using clay blended with sand, was determined in the laboratory. Water, sand and clay were blended to meet the laboratory determined specifications. The blended clay soils were added to the cells in two 7.5 cm thick lifts and compacted to 95% Proctor with a gasoline engine-powered vibratory compactor. Density and moisture measurements were determined after placement of each lift (Troxler 3411 Density Meter*). A 10 cm layer of fill sand and 4 perforated barrels were placed above the liners. Each cell was then backfilled to a dome shape to encourage rainfall runoff and covered with polyethylene.

The wastes to be placed in these field cells were dyed with Automate Red B and Fluorescent Yellow at 154 and 50 mg/l, respectively. About 1,400 liter of each waste was introduced into each cell through a standpipe on 1 of the 4 perforated barrels. Leachate was collected twice weekly by applying a vacuum to the collection manifold outlet and directing the liquid into 20 liter glass containers, from which it was measured and subsampled.

After the permeability was measured at 2 x 10^{-7} cm/sec or greater by calculation from the volume of cell drainage collected over time, each cell was disassembled. The fill soil and perforated barrels were carefully removed with a backhoe. The pallets, HDPE liners, and clay liners were lifted from the concrete cell by a crane. The HDPE sides were cut and removed to expose the compacted clay liners which were divided according to a randomized grid system and sampled for analysis.

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* Mention of trade names does not constitute endorsement.

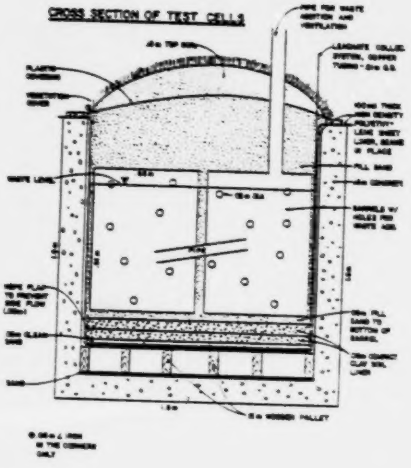

Figure 1. Schematic diagram of a crossection of a field cell.

Typically, 4 vertical profiles were sampled in 2.5 cm depth increments for chemical analysis, and 10 sample profiles were taken for morphological study. Additional samples were taken from readily observable cleavage planes, which were often colored by dye, and from cut surfaces representing the inside of single natural soil aggregates or peds.

Chemical Analysis

The determination of xylene in liner soil samples was accomplished by mixing the bulk soil-sample, taking a 25 g subsample, and blending the subsample with 50 ml of 20% CH_3OH:80%CH_2Cl_2 in an explosion proof Waring Blender. The mixture was filtered and brought to a 50 ml volume with CH_2Cl_2. An aliquot was then analyzed by a high performance liquid chromatography (HPLC - Beckman Model 3390) with a 4 mm "ultrasphere ODS" reverse phase column and 250 nm UV detector. The flow rate was 1 ml/min with 80:20 methanol:water as solvent system.

Analysis of leachate collected from the field cells for xylene was accomplished by measuring the volumes of the aqueous and organic phases after they separated.

For the determination of acetone in leachate samples, a 5 ml aliquot was transferred to a septum-capped vial and equilibrated at 25°C for 30 min. A 2 ml sample of the headspace was analyzed by flame ionization gas chromatography (GC, Tracor). Acetone in soils was determined by first mixing the bulk sample and selecting a 5 g subsample. The subsample was then transferred to a septum-capped vial and analyzed by GC as above. The GC was equipped with a 1.8 m x 4 mm id glass column packed with 30 cm of Porapak Q followed by 150 cm of 5% Carbowax 20 M on 80/120 Gas Chrom-Q. The conditions were as follows: N_2 carrier gas at 20 ml/min and the isothermal oven temperature at 40°C.

RESULTS AND DISCUSSION

Comparison of tests performed at different pressures and times was accomplished by plotting the calculated permeability as a function of the pore volume of effluent which passed through the liner.

Laboratory Results

The laboratory studies using the three soils at a series of pressures resulted in conclusions quite similar to those reported previously (Anderson et al., 1982; Brown and Anderson, 1983) for other soils and solvents. In most cases, the results from replicates were virtually identical with + 0.5 orders of magnitude. Only in cases where flow was too rapid to collect adequate data were major differences between replicates evident.

Representative data are shown in Figures 2 through 5. Permeabilities to water on similar soils were within + 0.25 orders of magnitude before solvents were introduced. After the solvents began to permeate the soil, the permeabilites increased, typically to values which were two to four orders of magnitude greater than those obtained with water. As can be seen by comparing Figures 2 and 3, the solvents broke through the clay soils at lower pore volumes when the soils were initially at the as-compacted moisture contents (nonsaturated), than when the soils were initially saturated with water. For the water-saturated soils, the pores were initially filled with water that had to first be displaced before the solvent could move through. Highest permeabilities measured on soils which were not presaturated were typically one or two orders of magnitude greater than those which were initially saturated.

Differences in the behaviors exhibited by polar and nonpolar solvents were the same as those seen previously (Anderson _et al_., 1982; Brown and Anderson, 1983). A comparison of break-through of the nonpolar xylene and polar acetone are shown in Figures 4 and 5b. The tests showed that the xylene rapidly increased the permeability of the clay soils after the cumulative flow exceeded 0.2 to 0.4 of a pore volume. Permeability changes caused by acetone characteristically resulted in a small decrease in permeability reaching the lowest value at 0.5 pore volume; this was followed by a subsequent increase in permeability. The different response to the polar acetone and nonpolar xylene is believed to be caused by acetone first causing swelling of the clay soil with low concentrations initially diffusing into the pores, followed by shrinkage when more of the water was displaced by the solvent.

Although data are still being collected for all replicates, it appears that hydraulic gradients used in conducting tests of permeability have little influence on either the increase in permeabilities observed or on the final permeability values achieved after the solvent penetrates the compacted soil mass. This conclusion is reached by comparing the data presented in Figures 5a-5c for kaolinitic clay exposed to acetone at three different hydraulic gradients. These data show a trend similar to others that have been collected (Anderson _et al_., 1982).

Increases in permeability as described in detail above were observed for all three soil types, but the data collected from bentonitic clay soils thus far did not exhibit an increase in permeability until a greater fraction of the pore volume was displaced than was necessary for the other soils.

Field Results

Permeability

The field studies are still in progress. However, within 12 months after installation, xylene had penetrated 10 of the 12 clay soil liners, while acetone had penetrated 2 soil liners. Permeability data for xylene are presented in Figures 6 to 8. The kaolinitic clay soil liner (Figure 6) shows a very clear, almost immediate increase in permeability. After passage of 1 pore volume of leachate through the compacted clay, the permeability had increased to an average of ~ 7 x 10^{-7} cm/sec. The largest permeability, replicate 1, was an order of

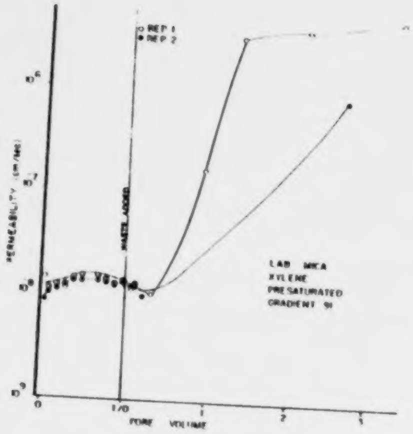

Figure 2. Permeability of presaturated soil (micaceous clay dominant) to xylene-rich waste. The tests were performed using a hydraulic gradient of 91.

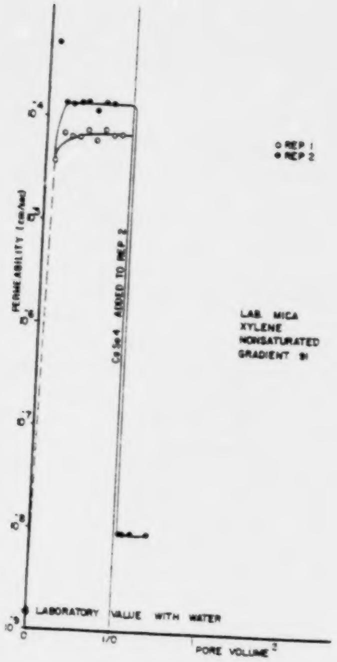

Figure 3. Permeability of nonsaturated soil (micaceous clay dominant) to xylene-rich waste and 0.01N $CaSO_4$ as a function of pore volume. The tests were performed using a hydraulic gradient of 91.

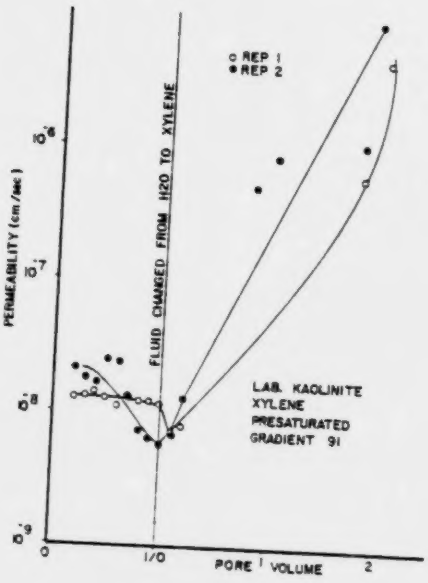

Figure 4. Permeability of presaturated soil (kaolinite clay dominant) to xylene as a function of pore volume. The tests were performed using a hydraulic gradient of 91.

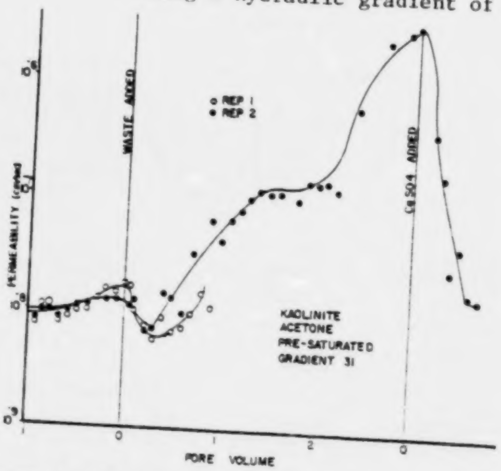

Figure 5a. Permeability of presaturated soil (kaolinite clay dominant) to acetone as a function of pore volume. The tests were performed using a hydraulic gradient of 31.

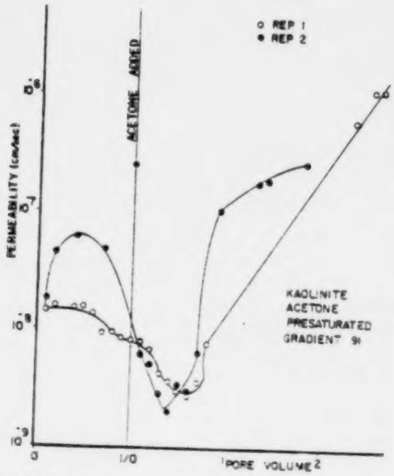

Figure 5b. Permeability of presaturated soil (kaolinite clay dominant) to acetone as a function of pore volume. The tests were performed using a hydraulic gradient of 91.

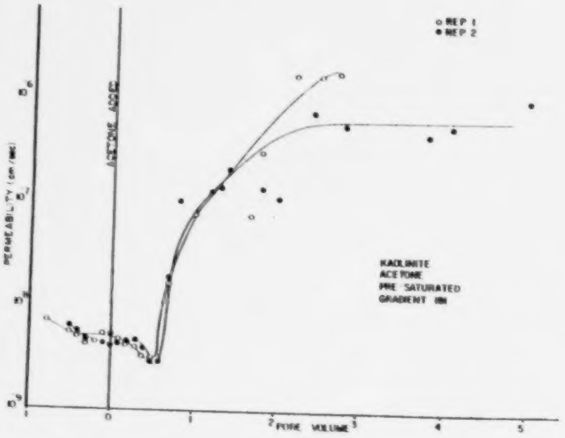

Figure 5c. Permeability of presaturated soil (kaolinite clay dominant) to acetone as a function of pore volume. The tests were performed using a hydraulic gradient of 181.

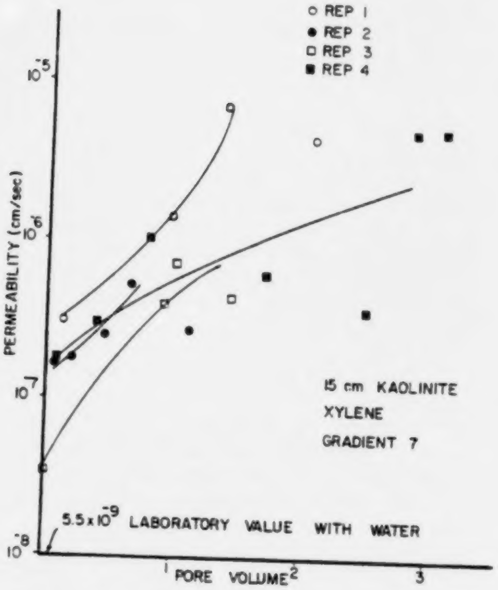

Figure 6. Permeability of kaolinite soil to xylene in a field test using a hydraulic gradient of 7.

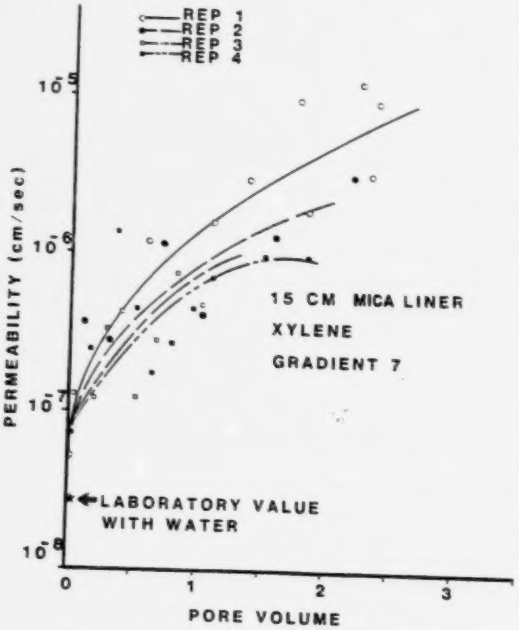

Figure 7. Permeability of a mica soil to xylene in field test using a hydraulic gradient of 7.

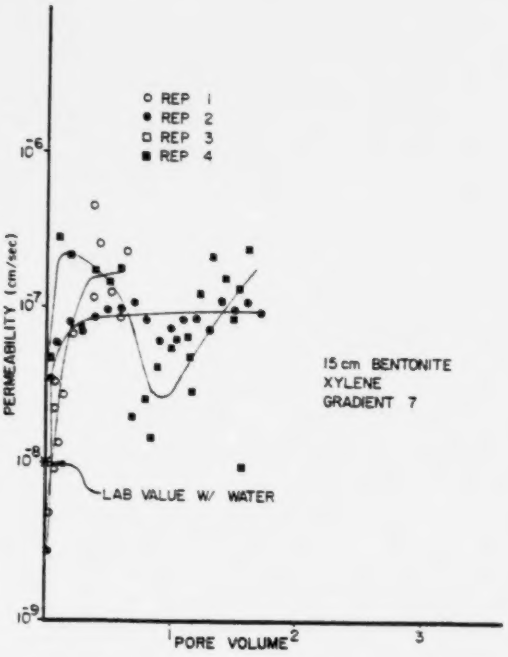

Figure 8. Permeability of bentonite soil to xylene in a field test using a hydraulic gradient of 7.

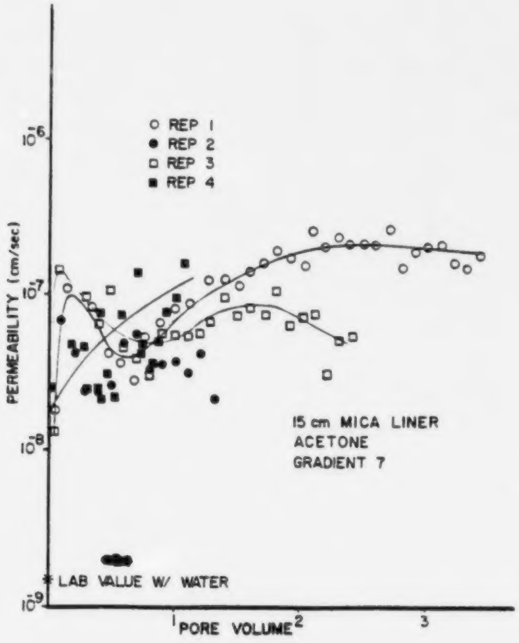

Figure 9. Permeability of mica soil to acetone in a field test using hydraulic gradient of 7.

magnitude above the average. Data from the micaceous clay soil liner (Figure 7) show a similar family of curves. Beginning permeabilities were well below 1 x 10^{-7} cm/sec. However, after the passage of 1 pore volume, the permeabilities had increased to 6 x 10^{-7} cm/sec. Most data is available for replicate 1 which continued to increase in permeability for the entire experimental period reaching 1 x 10^{-5} cm/sec.

Increases in permeability of the bentonitic clay soil liner (Figure 8) were more dramatic than that of the other two clays. Permeability of replicate 1 of the bentonitic clay soil liner was initially close to 1 x 10^{-9} cm/sec and very quickly rose to 2 x 10^{-7} cm/sec. Replicate 2 also exhibited a similar trend although not as dramatic an increase. The increases in permeability of as much as 2 orders of magnitude occurred in 0.5 of the pore volume as compared to 1 or more pore volumes required to cause a similar increase in the other clay soil liners.

The effect of acetone on the permeability of micaceous clay soil liners is shown in Figure 9. There was an initial decrease in permeability during the first 0.5 of a pore volume, after which there was an increase in permeability with final values greater than the initial permeability. This behavior appears to be characteristic of the impact of acetone on the permeability of compacted clay soils; this behavior has been consistently observed in both laboratory and field studies of all soils tested.

Morphology

The compacted clay soil liners in the field cells were carefully removed and dissected to allow for both visual inspection and photographic documentation of the exposed surfaces. The path of the xylene waste was much more evident than that of the acetone waste because of the presence of the paint pigments. When the HDPE was cut away at the level of the clay liner, it was evident in most cases that the waste had flowed along the sidewall next to the liner down to the level of the flap (See Figure 1). However, the clay liner adjacent to the sidewall was free of dye below the flap which indicated that the flap had functioned as planned in preventing the waste from bypassing the clay liner. Using a spade, the clay liner was cut in sections 10 cm thick. Wherever possible, large sections of the clay were broken free so that fracture planes that were likely to be paths of substantial flow would be exposed. In most instances, dye and pigments were evident on the surfaces of these cracks. The waste saturated the upper 1 or 2 cm of clay soil liners in nearly all the cells examined. In addition, it appeared, based on the dyed soil surfaces, that the waste moved to lower depths through preferential channels. When these channels reached the interface between the first and second lift, the waste generally spread out and permeated the lower 1 to 2 cm of the upper lift. Again, it appeared, based on dyed soil surfaces, that the waste then moved downward through preferential channels through the lower layer of compacted soil. Occasionally, preferential channels, the faces of which were coated with dye, were found to extend from the top to the bottom of the liner. When the soil mass was broken along spontaneously developed cleavage planes, vertical surfaces 10 to 20 cm wide were often coated with dye. It is not likely that the cracks resulted from dessication after compaction since care was taken to immediately cover all clay liners after compaction to prevent evaporation. The cracks observed were either present at the completion of compaction or were formed as a result of physical alteration of the clay by the wastes.

In all cases, dyed surfaces were found at apparently randomly developed spacings throughout the entire clay liner. This further indicated that the liquid moved through the bulk of the soil and did not bypass the liner. Morphology (macro scale) of all the soil mass comprising the liners could be described as massive, with few observed strong horizontal and vertical planes.

A system to impregnate soils, which had been penetrated with dyed wastes, was developed to allow polishing of thin sections (30 μm) for petrographic microscopic analysis. Preliminary photographs of the cross sections of the soils indicate that the waste moved through selected pores in the clay liners. Efforts are underway to develop automatic techniques to quantify these observations and permit larger numbers of sections to be more readily examined.

Chemical Concentrations

Typical xylene concentrations found in profile samples of each clay soil liner are presented in Table 3. The variability of concentrations occurring with depth in any one profile and across the clay soil liner at any given depth indicates that the movement of the liquid was through preferential pathways and did not move in a clearly defined wetting front through the entire soil mass. Some samples which

Table 3. Concentration of Xylene in μg/g in Soil Samples from a Typical Cell of the Three Different Clay Soil Liners.

Depth (cm)	Kaolinite Location No.†				Mica Location No.†			Bentonite Location No.†			
	1	2	3	4	1	2	3	1	2	3	4
0-2.5	235	18	44	170	237	112	51	533	16	4	71
2.5-5.0	1214	45	238	303	251	1027	105	5689	8	38	4
5.0-7.5	5060	333	806	122	584	1158	611	15969	31	685	1
7.5-10.0	352	419	564	36	714	4035	2031	23099	139	1520	822
10.0-12.5	13	12	71	160	1289	4310	77	29168	2585	1085	17785
12.5-15.0	9391	2	0	1669	204	1903	232	4144	4750	7272	1336
15.0-17.5	3757	722	2015	nd††	452	55	1887	12706	2409	7500	2542
17.5-20.0	3401	860	nd	nd	2005	nd	3952	20900	nd	11352	6960
20.0-22.5	nd	nd	nd	nd	nd	nd	4609	nd	nd	nd	nd

† randomly selected from 42 possible sample areas as determined by a grid system.
† † not determined.

had a volume of approximately 25 cm^3 at a particular location were nearly free of xylene, while others had contents as high as 20,000 mg/kg. Thus, large segments of the clay soil liner had little penetration by the solvent, while other adjacent segments were nearly saturated.

Similar evidence that xylene moved through the soil in cracks or around blocky sub-angular structural components of the liner is presented in Table 4 in which the xylene content of dyed and undyed surfaces of clay soil liner fragments are compared. The xylene content of the dyed surfaces exposed by breaking the liner along spontaneous cleavage planes in a given cell were typically at least 10 times greater than found in samples scraped from cut surfaces on which dye was not apparent. The lower xylene content of the undyed surfaces adds credence to the conclusion that xylene moved through preferential pathways, perhaps along cracks and ped faces, and not uniformly through the compacted clay soil mass.

Table 4. Xylene Content in mg/kg of Dyed and Undyed Surfaces (1 mm thick soil fragment surface) of Clay Soil Liners.

Lysimeter No.	Dyed Surface	Undyed
11	19,404	1,147
	9,149	0
	12,456	nd+
8	2,814	155
	2,691	704

+ not determined

Ongoing Studies

The present paper is a report of progress on an ongoing project, and several elements of the research remain to be completed. Approximately half of the field cells remain to be excavated, photographed, and sampled. Laboratory studies on the influence of dilutions of water soluble organics are presently being conducted. It is anticipated that further laboratory evaluations will include mixtures of organic wastes and testing of polymer-treated clays. Morphological studies to determine the effect of solvents on soil particle orientation and arrangement are also underway; efforts are being made to quantify the changes in pore size distribution which may occur as a result of organic liquid interactions with the soil. Other mechanisms of organic liquid-soil interactions which may explain the observations reported here are also being hypothesized and evaluated.

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LABORATORY STUDIES FOR DETERMINING FLEXIBLE-MEMBRANE SOIL BEDDING REQUIREMENTS

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ABSTRACT

Three laboratory tests were developed to simulate field loading conditions on flexible membrane liners during construction of hazardous waste landfills. One test method utilized a moving pneumatic tire loading, another used a rotating gyratory load, and the third used a cyclic vertical plate load. Loading conditions and thickness of cover material over the membrane were scaled using Boussinesq equations to produce vertical stresses on the membrane similar to those encountered under field conditions.

Test results showed that the moving pneumatic tire load test would be most useful for determining cover and bedding criteria using available site soils and candidate membranes. Also, a layer of clay soil was effective in preventing puncture of the membrane by the subgrade.

INTRODUCTION

Background

In recent years the Environmental Protection Agency (EPA) has sought means for limiting the hazards involved in disposal of industrial waste in landfills. The use of impervious flexible membrane placed over the subgrade in hazardous waste landfill could be a method of reducing the danger of toxic material from contaminating the soil and ground water. One problem with the use of membranes in waste landfills is that such membranes are subject to damage during construction and operation of the landfill. In November 1979, the EPA requested the U. S. Army Engineer Waterways Experiment Station (WES) to conduct a study aimed at determining an economical method for preventing damage to flexible membranes during construction and testing of prototype simulation of waste landfills utilizing various flexible membranes as liners. Twelve variations of membranes, subgrades, and protective covers were tested in this test series. The testing indicated that with a granular subgrade all of the membranes would sustain some damage during construction, but if a clay or a concrete sand were used as a subgrade, the damage would be reduced. The test data was reported in "Land Disposal: Hazardous Waste," Proceedings of the Seventh Annual Research Symposium, No. EPS-600/9-81-002, March 1981, edited by D. W. Shultz, Southwest Research Institute, San Antonio, TX 78284. Only a limited number of test items were evaluated in this study and results were variable. However, the test indicated a sand clay or silt (small grain size soil material) would be required under the membrane as well as on top of the membrane to protect the membrane from puncture caused by the action of the traffic to the surface and subgrade. At the conclusion of the initial phase of testing and after the results had been reported, the EPA requested that additional tests be conducted. In order to increase the number of tests that could be conducted and produce more consistent results, laboratory tests were devised that would simulate field testing.

Test Objective

The objective of this investigation was to develop laboratory tests that could be used to determine soil cover and bedding requirements for protecting flexible membrane liners from puncture during construction of hazardous waste landfills.

Scope of Work

Three laboratory tests were developed to simulate field loading conditions on flexible membrane liners during construction of hazardous waste landfills. One test used a moving pneumatic tire loading, another used a rotating gyratory load, and the third used a cyclic vertical plate load. Tests were conducted using a gravelly sand or limestone subgrade under the membrane liner and a gravelly sand cover. In some tests, a lean clay or a fabric was placed between the liner and subgrade to serve as protection for the membrane liner. One type and thickness of cover and three membrane liners were used in the tests. Other special tests were conducted to develop a test that possibly could be used as a screening test for membrane liners.

Definitions

Cover material: Material placed on top of a membrane liner to protect the liner from puncture during construction of a landfill.

Bedding material: Material placed between the membrane liner and the subgrade to protect the liner from puncture.

Subgrade: Soil used in these tests to represent natural material upon which a landfill may be constructed.

DEVELOPMENT OF MODEL PARAMETER

Vertical stresses on the membrane were selected as the modeling parameter in the laboratory test to simulate the field test. It was felt that this was an important parameter affecting the behavior of the membrane and one that could be translated from the field to the laboratory. The stress on the membrane is basically dicated by the type and magnitude of the load, surface contact pressure, and thickness of the cover over the membrane. The estimated stress on the membrane for cover thickness of 15.2, 30.5, and 45.7 cm (6, 12, and 18 in., respectively) used in the field tests were 206.7, 158.5, and 110.2 kilopascals, respectively (30, 23, and 16 psi, respectively). The laboratory tests were designed to duplicate these stresses on the membrane at a 15.2-cm (6-in.) depth by calculating that loading which would produce the desired stress. These calculations were made using Boussinesq equations for stress which is an accepted geotechnical procedure. A schematic drawing showing the general arrangement of the layers during testing is presented in Figure 1.

DESCRIPTION OF EQUIPMENT AND TESTS

General

Three types of test equipment were selected for testing the membranes. One consideration was that the equipment be readily available to most commercial-type laboratories, or be easily obtained, and that it be adaptable for testing membrane materials. The initial tests were conducted using the plate loading equipment since this method has been used to test fabrics used as reinforcement in pavements. The gyratory tests were conducted next since they required a small sample and were easy to conduct. The pneumatic tire tests were conducted last and required the development of test equipment to simulate the effects of a moving tire load. The various types of equipment are described below.

Pneumatic Tire Load

The model load cart and soil test box are shown in Figure 2. The load cart was moved for tracking purposes by the force generated by an air cylinder on a ram that moved through a maximum travel distance of 61 cm (24 in.). The load wheel was capable of being maneuvered into three different positions in the soil box for traffic test purposes. A total load of 3.5 kilonewtons (800 lb) was positioned on

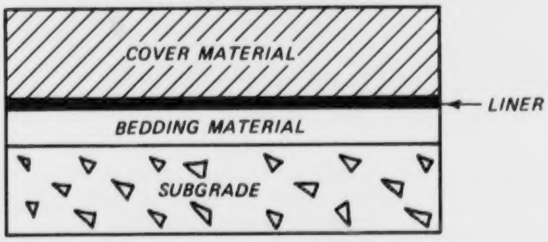

Figure 1. Typical test sample.

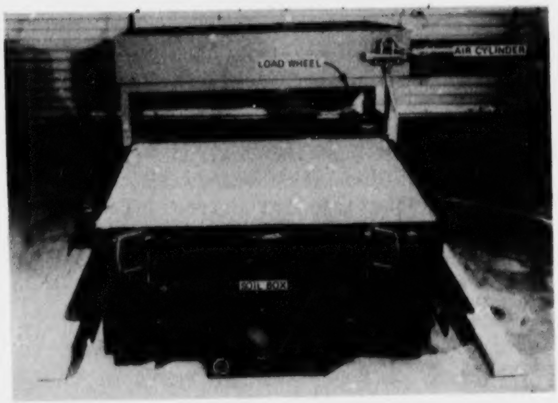

Figure 2. Testing equipment for pneumatic wheel load tests.

the load cart and the 5.00-5, 4-ply tire inflated to 220.5 kilopascals (32 psi). The dry weight and water content were determined for the soil used for each of four lifts. Each lift was compacted by hand tamping to produce the density desired. Following this, the membrane was placed taut over the subgrade and the 3.2-cm- (1.25-in.-) deep collar was C-clamped in position to confine the sand cover. The tracking lanes were 10.2 cm (4 in.) wide by 70 cm (24 in.) long; however, only the center 35.6 cm (14 in.) of the lanes were used for comparison purposes (Figure 3). The ends of the tracking lanes were not used for evaluating punctures as the load was shifted in this area when the cart direction was reversed. Sand was placed, compacted, and leveled in the box collar and on top of the membrane as a cushion (Figure 2). Three tracking lanes (three tests) were available for traffic tests each time the soil box was filled with soil. After three tests were conducted, the top 15.2 cm (6 in.) of subgrade material was reworked and/or replaced, and recompacted for additional traffic tests. In some tests, 2.5 cm (1 in.) of the subgrade was replaced with a lean clay to protect the membrane from puncture.

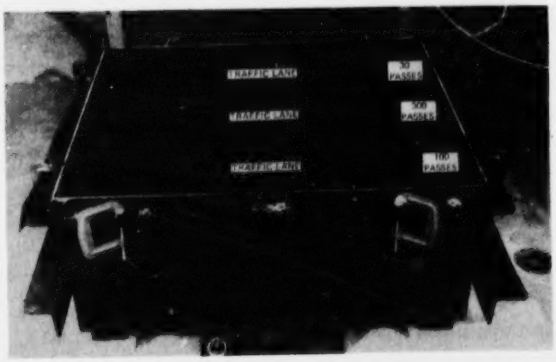

Figure 3. M3 membrane placed over compacted soil collar for sand clamped in place and tracking lanes marked.

Gyratory Shear

The gyratory shear test was conducted in the gyratory testing machine shown in Figure 5. In this test a vertical load is applied by a piston to a material sample contained in a tilted mold. By applying a rotating load to the mold, shear strain is induced throughout the sample. The combined action of the vertical stress and the shear strain is similar to the kneading action of a rolling tire load. During the test, the applied load (pressure) tilt or angle of gyration (usually 1 degree) and number of revolutions are controlled.

Two types of subgrade were used in these tests. One was the same crushed limestone used with the model load cart tests and the other subgrade was a 5.1-cm- (2-in.-) thick rubber block with a California bearing ratio (CBR) value of 16. The rubber subgrade contained steel barbs at the surface to simulate rocks. Three of the barbs were 0.6, 1.3, and 0.9 cm

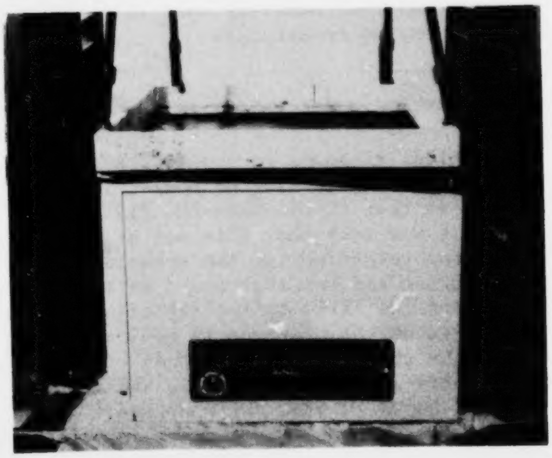

Figure 4. Soil box for plate loading tests.

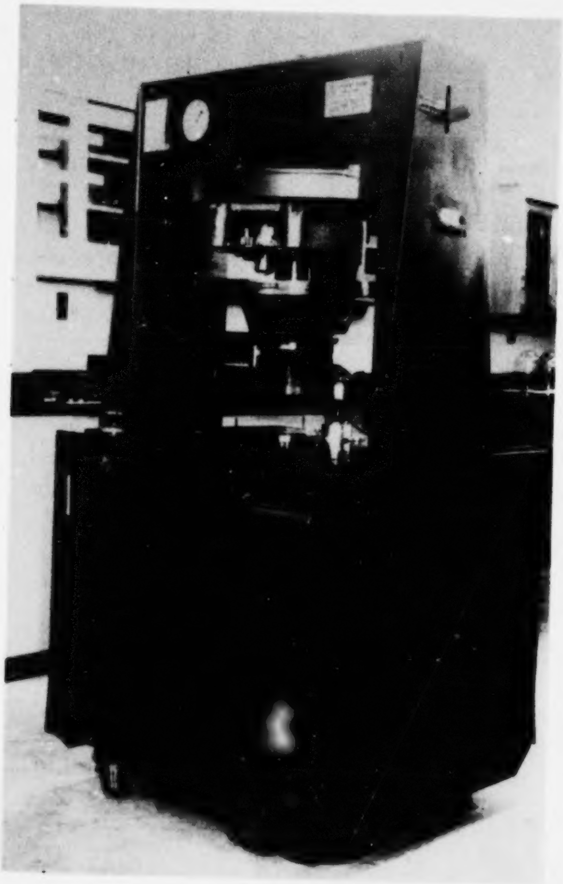

Figure 5. Gyratory compaction machine.

Figure 6. Overall view of Instron, recorder and soil membrane test setup.

(0.25, 0.5, and 0.37 in., respectively) high with a conical angle of 60 degrees, radius of the apex angle of 0.04 cm (0.015 in.). Another 0.6-cm- (0.25-in.-) high barb had a 0.08-cm (0.03-in.) radius at the apex angle; one had a 0.15-cm (0.06-in.) radius, and the last one was a half sphere with a 0.6-cm (0.25-in.) radius referred to as smooth. The test membranes with a sand cover were placed above the subgrades of both type samples. In tests where a lean clay was used, 2.5 cm (1 in.) of the subgrade was replaced with the clay as a bedding to protect the membrane from puncture.

Plate Loading

The plate load tests were performed using the Instron equipment (Figure 6). The load was applied to a 29.2-cm- (11.5-in.-) diam steel plate, 2.5 cm (1 in.) thick. A cyclic load of 1.48 kilonewtons (3324 lb) was applied to the 668.8-sq-cm (103.7-sq-in.) plate to achieve 220.5-kilopascal (32-psi) pressure to the sand-covered membrane. The soil box 0.6 by 0.6 by 0.45 m (2 by 2 by 1.5 ft) deep was filled with gravelly sand and compacted in four layers. Gradation of the gravelly sand is shown in Figure 7. Each layer of soil was weighed and compacted in a known volume to produce the desired density. The water content was controlled prior to compaction and the density and water content measured with the Troxler Nuclear Densitometer after compaction. The membrane and collar (6.4 cm (2.5 in.) deep to confine the concrete sand) was clamped in place followed by the addition of the concrete sand which was tamped and leveled (Figure 4).

The cyclic load was applied at a rate of 10-12 cycles per minute to a maximum of

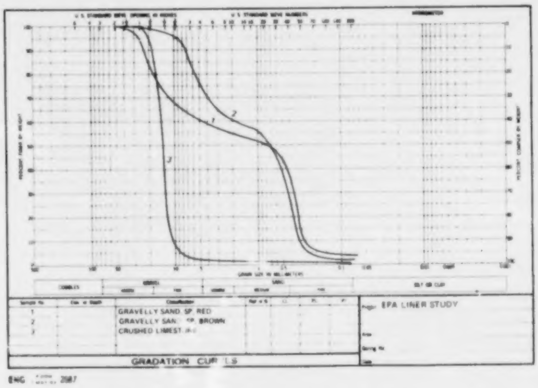

Figure 7. Soil gradation curves.

1000 cycles. After a varied number of cycles had been applied (300, 400, or 500 cycles) the membrane was removed, inspected, and punctures marked. The membrane was then replaced as nearly as possible in its original test position with the collar and sand cover replaced and the test continued. The subgrade after these cyclic loads were applied was not disturbed or replaced. As additional tests were conducted, only the top 15.2 cm (6 in.) of the subgrade was scarified and recompacted.

DESCRIPTION OF MATERIALS

Soils

The soils selected for use in testing the membranes were as follows:

- a. A brown gravelly sand (SP) (classified by Unified Soil Classification System) having a gradation as shown on Figure 7 was used as a cover to protect the membrane during tests. Only the material that passed the 0.9-cm (0.37-in.) sieve was used for test purposes.
- b. A red gravelly sand (SP) having a gradation as shown on Figure 7 was used as a subgrade material.
- c. A lean clay (CL) was used as a bedding material.
- d. A crushed limestone with approximately 85 percent of the aggregate between the 1.9-cm (0.75-in.) and 0.9-cm (0.37-in.) screens. The crushed limestone gradation curve is shown on Figure 7.

Soil data for the wheel load tests are shown in Table 1.

Membranes

Three membranes tested during this investigation as well as a geotextile used as bedding material were used in the laboratory tests and are described as follows:

Designation	Polymer	Nominal Thickness mm (mils)	Thread Count
M2	Polyvinyl chloride (PVC)	0.51 (20)	*
M3	Chlorinated polyethylene (CPE)	0.76 (30)	*
M4	Chorosulfated polyethylene-reinforced (CSPE-R)	0.91 (36)	10x10
B1	Spunbonded continuous polyester filament, 261.1 g/sq m (7.7 oz/sq yd)	2.06 (81)	*

* Not applicable.

FAILURE CRITERIA AND DATA COLLECTED

Failure Criteria

The criteria used to determine membrane liner failure consisted of the visual inspection of pinholes in the membrane liner caused by tests and then the examination of the pinholes in accordance with ASTM Test Method D 3083. When light used in accordance with the ASTM Test Method was observed to pass through any one of the pinholes, this was identified as failure of the membrane liner.

TABLE 1. SOIL DATA FOR WHEEL LOAD TESTS

Test No.	Soil Type	Soil Use	Oven Water Content percent	Troxler* Nuclear Test	
				Water Content percent	Wet Density kilonewtons/cu m (lb/cu ft)
W1	Concrete sand	Cover	3.5	--	-- --
	Gravelly sand	Subgrade	5.9	7.0	20.7 (131.5)
W2	Concrete sand	Cover	3.2	--	-- --
	Gravelly sand	Subgrade	--	6.8	21.0 (133.5)
W3	Concrete sand	Cover	3.7	--	-- --
	Gravelly sand	Subgrade	--	6.0	21.2 (135.0)
W4	Concrete sand	Cover	3.5	--	-- --
	Gravelly sand	Subgrade	--	6.4	20.8 (132.4)
W5	Concrete sand	Cover	4.9	--	-- --
	Gravelly sand	Subgrade	--	6.4	20.8 (132.4)
W6	Concrete sand	Cover	3.7	--	-- --
	Clay (loess)	Bedding	19.4	--	-- --
	Gravelly sand	Subgrade	--	6.5	21.0 (134.0)
W7	Concrete sand	Cover	4.6	--	-- --
	Gravelly sand	Subgrade	--	6.0	20.8 (132.1)
W8	Concrete sand	Cover	4.4	--	-- --
	Gravelly sand	Subgrade	--	6.0	20.8 (132.1)
W9	Concrete sand	Cover	4.4	--	-- --
	Gravelly sand	Subgrade	--	5.9	20.7 (132.0)
W10	Concrete sand	Cover	4.8	--	-- --
	Gravelly sand	Subgrade	--	6.2	20.8 (132.6)
W11	Concrete sand	Cover	4.2	--	-- --
	Gravelly sand	Subgrade	--	6.2	20.8 (132.6)
W12	Concrete sand	Cover	4.4	--	-- --
	Gravelly sand	Subgrade	--	6.1	20.8 (132.7)
W13	Concrete sand	Cover	4.5	--	-- --
	Gravelly sand	Subgrade	--	6.1	20.8 (132.7)
W14	Concrete sand	Cover	3.9	--	-- --
	Clay (loess)	Bedding	18.3	--	-- --
	Gravelly sand	Subgrade	6.0	5.3	20.8 (132.7)
W15	Concrete sand	Cover	3.7	--	-- --
	Clay (loess)	Bedding	19.2	--	-- --
	Gravelly sand	Subgrade	--	5.7	20.9 (133.3)

(Continued)

*Device used to expedite water content and density determinations.

TABLE 1. (CONCLUDED)

Test No.	Soil Type	Soil Use	Oven Water Content percent	Troxler Nuclear Test: Water Content percent	Troxler Nuclear Test: Wet Density kilonewtons/cu m (lb/cu ft)
W16	Concrete sand	Cover	3.5	--	-- --
	Clay (loess)	Bedding	18.0	--	-- --
	Gravelly sand	Subgrade	5.5	6.1	21.0 (133.8)
W17	Concrete sand	Cover	3.5	--	-- --
	Limestone	Subgrade	--	--	15.7 (100.0)
W18	Concrete sand	Cover	3.5	--	-- --
	Clay (loess)	Bedding	23.2	--	-- --
	Limestone	Subgrade	--	--	15.7 (100.0)
W19	Concrete sand	Cover	3.5	--	-- --
	Clay (loess)	Bedding	18.1	--	-- --
	Limestone	Subgrade	--	--	15.7 (100.0)
W20	Clay (loess)	Bedding	18.1	--	-- --
	Limestone	Subgrade	--	--	15.7 (100.0)

Data Collected

The number of punctures were recorded for selected levels of load repetitions. The general condition of the membrane was noted such as scuffed or wrinkled, etc., and photographs were made to illustrate these conditions. The number of loading cycles, passes, revolutions, plus the total weight applied, and tire pressure also were recorded. The density and water content of the subgrade material along with the CBR of the clay bedding material were controlled. In the pneumatic tire model test, the rut depth, soil upheaval, and cover over the membrane also were recorded at regular intervals.

TEST RESULTS

Pneumatic Tire Load

After the tire had traversed back and forth in the same path for the desired number of passes, the rut depth, shoulder upheaval, and the depth of sand over the membrane were measured. When the tire had tracked the test specimens, the collar and sand were removed and the membrane inspected for punctures. The test number, membrane designator, passes, rut depth, membrane depth below rut, number of punctures in the membrane, subgrade deformation, and soil data are given in Tables 1 and 2.

A minimum of three tests per membrane was performed on each soil subgrade and cover material. These test results indicate that punctures occurred to some of the membranes from the subgrade rocks and the membrane needed some bedding or protection from the subgrade. Hence, tests W14, W15, and W16 were repeats of the W2, W3, and W4 tests for M2 membrane, except the top 2.5 cm (1 in.) of the gravelly sand subgrade was replaced with a lean clay (loess). The clay was used as a bedding material to prevent the gravelly subgrade from puncturing the membrane during traffic tests.

Test W17 was conducted first on a crushed limestone base that readily produced punctures in the membrane. Then the test was repeated using 2.5 cm (1 in.) of a lean clay (loess) as the top layer of the subgrade. The 2.5 cm (1 in.) of lean clay was used above the limestone in tests

TABLE 2. TRAFFIC DATA FROM WHEEL LOAD TESTS

Membrane	Test No.	Number of Passes	Rut Depth* cm (in.)	Membrane Depth Below Rut cm (in.)	Subgrade Deformation cm (in.)	No. of Punctures	Remarks
M2	W1	10	-- --	0.63 (0.25)	-- --	0	
		30	3.18 (1.25)	0.46 (0.18)	-- --	0	
		100	3.81 (1.50)	0.63 (0.25)	-- --	4	1 puncture from top down
M2	W2	30	3.18 (1.25)	0.79 (0.31)	-- --	0	
		100	3.18 (1.25)	0.63 (0.25)	-- --	0	
		300	3.96 (1.56)	0.63 (0.25)	-- --	10	
M2	W3	30	2.39 (0.94)	0.79 (0.31)	-- --	0	
		100	2.84 (1.12)	0.63 (0.25)	-- --	1	
		300	3.33 (1.31)	0.63 (0.25)	-- --	9	
M2	W4	30	2.69 (1.06)	0.79 (0.31)	-- --	0	
		100	2.99 (1.18)	0.46 (0.18)	-- --	3	
		300	2.69 (1.06)	0.46 (0.18)	-- --	8	3 or 4 holes from top down
M2	W5	100	3.18 (1.25)	0.63 (0.25)	-- --	1	Undisturbed subgrade of test W4 used; geotextile under membrane
		300	3.18 (1.25)	0.63 (0.25)	-- --	6	
		500	2.99 (1.18)	0.46 (0.18)	-- --	2	
M2	W6	100	3.48 (1.37)	0.63 (0.25)	-- --	0	Top 2.5 cm (1 in.) of subgrade material was in lean clay
		300	2.54 (1.00)	0.46 (0.18)	-- --	0	
		500	3.18 (1.25)	0.63 (0.25)	-- --	0	
M3	W7	30	2.84 (1.12)	0.90 (0.37)	-- --	0	
		100	2.99 (1.18)	0.46 (0.18)	-- --	1	
		300	3.18 (1.25)	0.63 (0.25)	-- --	5	
M3	W8	30	2.06 (0.81)	0.79 (0.31)	-- --	0	
		100	2.69 (1.06)	0.63 (0.25)	-- --	0	
		300	2.84 (1.12)	0.46 (0.18)	-- --	7	
M3	W9	30	2.39 (0.94)	0.79 (0.31)	-- --	0	
		100	2.39 (0.94)	0.63 (0.25)	-- --	1	
		300	3.48 (1.37)	0.46 (0.18)	-- --	1	
M4	W10	30	2.69 (1.06)	0.79 (0.31)	-- --	0	
		100	2.84 (1.12)	0.46 (0.18)	-- --	0	
		300	2.54 (1.00)	0.46 (0.18)	-- --	0	
M4	W11	30	2.21 (0.87)	0.79 (0.31)	-- --	0	
		100	2.54 (1.00)	0.63 (0.25)	-- --	0	
		300	2.54 (1.00)	0.46 (0.18)	-- --	0	
M4	W12	30	2.84 (1.12)	0.63 (0.25)	-- --	0	
		100	2.54 (1.00)	0.63 (0.25)	-- --	0	
		300	3.18 (1.25)	0.63 (0.25)	-- --	1	
M3	W13	30	1.57 (0.62)	0.63 (0.25)	-- --	0	
		100	3.18 (1.25)	0.46 (0.18)	-- --	1	
		300	2.54 (1.00)	0.63 (0.25)	-- --	11	

(Continued)

*Depth from original surface to bottom of rut.

TABLE 2. (CONCLUDED)

Membrane	Test No.	Number of Passes	Rut Depth cm (in.)	Membrane Depth Below Rut cm (in.)	Subgrade Deformation cm (in.)	No. of Punctures	Remarks
M2	W14	300	3.48 (1.37)	0.46 (0.18)	1.27 (0.50)	0	
		500	3.66 (1.44)	0.63 (0.25)	0.63 (0.25)	2	
		1000	3.18 (1.25)	0.46 (0.18)	0.90 (0.37)	3	
M2	W15	300	2.69 (1.06)	0.46 (0.18)	0.63 (0.25)	0	
		500	3.96 (1.56)	0.46 (0.18)	0.79 (0.31)	0	Membrane wrinkled in ruts
		1000	4.14 (1.63)	0.79 (0.31)	1.27 (0.50)	0	
M2	W16	300	3.96 (1.56)	0.46 (0.18)	1.57 (0.62)	0	Rocks 0.79 cm (0.31 in.), 1.1 cm (0.44 in.), and 0.63 cm (0.25 in.) below loess at 300, 500, and 1000 passes respectively
		500	3.81 (1.50)	0.46 (0.18)	1.27 (0.50)	0	
		1000	3.81 (1.50)	0.46 (0.18)	1.90 (0.75)	2	
M2	W17	10	2.84 (1.12)	1.27 (0.50)	-- --	3	
		30	2.54 (1.00)	0.63 (0.25)	1.57 (0.62)	19	
		100	4.75 (1.87)	0.63 (0.25)	1.90 (0.75)	30	
M2	W18	50	4.45 (1.75)	1.57 (0.62)	5.08 (2.00)	0	
		150	5.87 (2.31)	1.42 (0.56)	7.62 (3.00)	0	Clay too wet
		300	6.35 (2.50)	1.27 (0.50)	8.89 (3.50)	2	
M2	W19	50	3.18 (1.25)	0.63 (0.25)	-- --	0	
		150	3.18 (1.25)	0.63 (0.25)	-- --	0	
		300	2.84 (1.12)	0.15 (0.06)	-- --	0	
M2	W20	300	-- --	0	-- --	0	Same as test W19 except no concrete sand cover used
		500	-- --	0	-- --	0	

W18 and W19. Where the clay was used, no punctures were observed at 150 passes; whereas, in test W17, 36 punctures were recorded at 100 passes without the clay. The clay in test W18 had 22.2 percent water and a CBR of 1.8 that permitted excessive rutting, and after 300 passes, two punctures were observed in the M2 membrane. Test W19 was conducted similarly to test W18 except the water content of the clay was 18.1 and the CBR was 21. The higher CBR prevented excessive rutting and no punctures were observed in the M2 membrane after 300 passes as compared to 36 punctures recorded at 100 passes in test W17 without the clay bedding. Test W20 was conducted on the same subgrade as test W19 (not reworked) with no sand cover on the membrane (the tire was in direct contact with the M2 membrane), but only two tracking lanes were used and no punctures were observed after 500 passes.

Test W5 was conducted on the same subgrade (not reworked) as test W4. A geotextile (material B1) was placed on the top of the subgrade to see how effective it was as a bedding material to prevent punctures in the membranes. The membrane was placed directly on top of the geotextile and 3.2 cm (1.25 in.) of protective sand was placed on top of the membrane. The geotextile reduced the number of punctures at 100 and 300 passes from 3 to 1 and 8 to 6, respectively. The lean clay used in test W6 produced the first laboratory test results that indicated lean clay used as bedding placed over coarse subgrade composed of angular particles will reduce or prevent pneumatic-tired traffic from producing punctures to a membrane liner.

Gyratory Shear

A small simple-to-prepare sample is required for this machine, and the loading and operation are relatively easily and quickly performed. Extensive testing and previous experience with this laboratory equipment made it appropriate for use in this study. The initial membrane test samples were prepared with a subgrade that consisted of a well-graded crushed limestone (Figure 7) except the material retained on the 1.9-cm (0.75-in.) sieve was not used. The rough irregularly shaped limestone was used with the expectation of producing punctures in the membrane after a small number of revolutions, as no bedding was used in these initial tests. Results of these tests are shown on Table 3. Tests G1 and G5 were duplicates used to determine reproducibility of test data. These tests were found to produce reasonably close results as 20 and 17 punctures were counted after 10 revolutions. The same test materials were used in test G6 except the top 2.5 cm (1 in.) of the limestone was replaced with lean clay. After 500 revolutions, no punctures were observed in the M2 membrane specimens; whereas, 20 and 17 punctures had occurred previously after 10 revolutions in tests G1 and G5, respectively.

Tests G2, G3, and G4 were conducted on the M4 membrane for comparison with test results on the M2 membrane. After 10, 30, and 100 revolutions, there were 0, 1, and 0 punctures, respectively, in the M4 membrane. Test G7 was identical to test G6 except there was no sand cover placed over the membrane (the steel upper head of the gyratory machine was in direct contact with the membrane). After 500 revolutions, there were no punctures in the M2 membrane.

Plate Loading

Results of the plate loading tests are presented in Table 4. Four tests were run on the M2 membrane, and three each on the M3 and M4 membranes. The initial test consisted of 1000 cycles of loading which resulted in 3 punctures of the M2 membrane on the SP subgrade. The cover material and liner were removed and a geotextile placed on the undisturbed subgrade of test P1. The liner was placed on top of the geotextile and covered with 6.4 cm

TABLE 3. GYRATORY TEST RESULTS OF MEMBRANES PLACED ON CRUSHED LIMESTONE (1.9 CM (0.75 IN.))

Test Number	Cover Soil	Revolutions	Membrane	Number of Holes	Remarks
G1	Concrete sand	10	M2	20	
G2	Concrete sand	10	M4	0	Numerous abrasions noted
G3	Concrete sand	30	M4	1	Numerous abrasions noted
G4	Concrete sand	100	M4	0	Numerous abrasions noted
G5	Concrete sand	10	M2	17	
G6	Concrete sand	500	M2	0	Layered sample from bottom to top as follows: 5.1 cm (2 in.) limestone plus 2.5 cm (1 in.) lean clay at 18 percent moisture, plus M2, plus 5.1 cm (2 in.) concrete sand at 3.5 percent moisture
G7	None	500	M2	0	Layered samples from bottom to top as follows: 10.2 cm (4 in.) limestone, plus 2.5 cm (1 in.) lean clay at 18 percent moisture, plus M2

TABLE 4. PLATE LOADING TEST DATA

Test	Membrane	Number of Cycles	Number of Holes	Remarks
P1	M2	300	0	
		1000	3	One puncture caused by a sharp rock one by a flat rock, and the other in a generally smooth area appeared to occur from the top in a downward direction
P2	M2	500	0	Geotextile placed over undisturbed subgrade of test P1 that produced 3 holes at 1000 cycles
		1000	0	
P3	M2	400	3	Two holes caused by a large flat rock under the membrane.
		1000	5	Holes at 400 cycles did not increase in size
P4	M2	400	7	
		1000	8	Several holes increased in size at 1000 cycles
P5	M3	300	0	
		1000	7	
P6	M3	400	0	
		1000	3	
P7	M3	500	0	
		1000	0	
P8	M4	400	0	
		1000	0	
P9	M4	500	0	
		1000	0	
P10	M4	1000	0	

(2.5 in.) of sand. After 1000 cycles of loading, no punctures appeared in the membrane indicating that the geotextile was effective in protecting the membrane. Test P1 was duplicated in tests P3 and P4 to provide more than one test point. These tests produced punctures at 400 cycles indicating that the punctures in test P1 may have occurred shortly after the 300 cycles at which data was obtained.

Membrane M3 sustained several punctures at 1000 cycles in tests P5 and P6, but not in P7. There also were no punctures at the intermediate number of cycles where data was taken. Membrane M4 sustained no punctures in tests P8, P9, and P10 at 1000 cycles of loading.

In all of these tests, the water content and dry density of the gravelly sand subgrade was controlled at an average of 6.8 percent and 19.5 kilonewtons/cu m (124.1 lb/cu ft), respectively. The cover sand had an average water content of 3.9 in all plate load tests.

ANALYSIS OF DATA

Pneumatic Tire Load

As indicated in Table 2, nine tests were run on the M2 membrane over an SP subgrade. Four tests (W1-W4) were repetitive having similar test conditions and results. Each of these tests sustained no punctures at 10 passes of the wheel load, a minimum number of punctures at 100 passes of the wheel load, and several punctures at 300 passes of the wheel load. The number of punctures seemed to be directly related to the number of rocks in contact with the membrane. Therefore, in order to prevent puncture of the membrane, it was necessary to provide a protective layer of material that would prevent membrane from coming in contact with the rocks in the subgrade. Two different methods were tried, one being placement of a nonwoven geotextile between the membrane and the SP subgrade, and the other being the placement of a layer of clay soil between the membrane and subgrade.

Test W5 shows the test results using the geotextile as a bedding material above the subgrade. As can be seen in Table 2, punctures occurred at all pass levels where observations were made. However, a comparison of punctures at the different pass levels indicates that the geotextile was effective in reducing the number of punctures.

Test W6 shows the test results using 2.5 cm (1 in.) of lean clay as a bedding material above the subgrade. The lean clay was very satisfactory in that no punctures occurred in the M2 membrane at any level where observations were made. To further demonstrate the effectiveness of the clay bedding, three more tests were run at higher pass levels using the M2 membrane. These tests (W14-W16) also showed no punctures at 300 passes of the wheel load. However, a few punctures developed at 500- and 1000-pass levels in test W14 and at 1000 passes in test W16. Test W15 produced no punctures at 1000 passes. These tests again show the effectiveness of a clay bedding for at least 300 wheel load passes.

Since the clay material had been effective on the gravelly sand subgrade, it was decided to test it on a very severe condition using crushed limestone as a subgrade. Test W17 shows the severity of the crushed limestone on the membrane in that 36 punctures were produced at 100 passes. Tests W18-W20 were then run using the lean clay as a bedding material over the limestone and below the membrane. In all three tests, the lean clay prevented punctures up to 300 passes except for test W18 which sustained 2 punctures due to the clay being too soft. Test W20, which had no cover over the membrane, went up to 500 passes without any punctures. These tests also demonstrated the effectiveness of the lean clay in preventing punctures even under very severe conditions. For maximum protection of the membrane, the lean clay should be compacted adequately to prevent rutting (water content on dry side of optimum).

The initial tests run on the M2 membrane were repeated using the M3 membrane and the M4 membrane. These tests consisted of the concrete sand cover over the membrane and the gravelly sand subgrade under the membrane. Tests on the M3 membrane produced results similar to the M2 membrane; therefore, additional tests were not considered necessary using the geotextile or the clay bedding. The test results using the M4 membrane were significantly better than tests on the M2 or M3 membrane with only one puncture being produced in the three tests at 300 passes. Since this is the stronger of the membranes, it was considered that the bedding requirements for the M2 also would be satisfactory for the M4. The pneumatic tire load test would be a useful test for determining cover and bedding requirements using available site soils and candidate membranes.

Gyratory Tests

Results of the gyratory tests using a crushed limestone subgrade are shown in Table 3. This was considered a severe test for the membrane materials, and as expected, numerous punctures were produced in the M2 membrane when placed on the crushed stone with the concrete sand cover as shown by tests G1 and G5. The number of punctures was reduced to zero when the membrane was protected from the crushed stone by a 2.5-cm (1-in.) layer of lean clay as indicated by tests G6 and G7. Tests on the M4 membrane showed that it had greater resistance to puncture, as only one puncture occurred during three different tests (G2, G3, and G4). Numerous abrasions were noted on the M4, and indications were additional cycles may have produced punctures from these abrasions.

Plate Loading Tests

Results of the plate loading tests are shown in Table 4. The plate tests did not develop failures in the membrane as had been observed in previous field tests or as produced by pneumatic tire load and gyratory tests. The plate loading tests indicated that the fabric prevented punctures to the membranes, but in field tests and the model tire tests, the fabric was not as effective in preventing punctures.

COMPARISON WITH FIELD TESTS

At the present time, only general observations have been made in comparing the laboratory test results with field test results. In the field tests reported in the Seventh Annual Research Symposium, punctures in the membranes occurred regardless of the thickness of cover over the membranes. Punctures probably occurred because the membranes were directly on top of the granular subgrades and were in contact with gravel particles. Where the sand and sandy silt subgrade was used, the number of punctures was reduced and was zero for some membranes. These results compare favorably with the results of the pneumatic tire tests conducted in the laboratory which showed that separating the membrane from the granular material by a lean clay will prevent or reduce punctures in the membrane. In the laboratory tests, the fabric bedding material prevented or reduced the number of punctures in all tests. There also was some indication in the field tests that the use of a fabric under the liner may protect the liner from puncture, although not all field tests indicated this.

CONCLUSIONS

Based upon the results of this study, the following conclusions are considered warranted:

a. The pneumatic wheel load tests would be the most useful test for determining cover and bedding criteria using available site soils and candidate membranes.

b. Liner material must be protected from the top by a cover material and from the bottom by a bedding material.

c. The cover material placed above a liner as well as the bedding material should be a soil classified as a clay, silt, or sand and having a gradation similar to the clay or concrete sand used herein. Material should have no particles larger than 0.9 cm (0.37 in.).

d. The 2.5 cm (1 in.) of lean clay bedding material was effective in preventing puncture of the liner material by the gravel subgrade.

e. Use of the geotextile as a bedding material reduced the number of punctures and use of a thicker geotextile may prevent punctures from occurring.

APPLICATIONS OF GEOTEXTILES IN LAND WASTE DISPOSAL SITES

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ABSTRACT

This paper provides those involved with the land disposal of solid and hazardous waste with an introduction to geotextiles. It is part of an overall program to provide design criteria, preferred construction methods and basis for cost comparisons for the use of geotextiles in land disposal of solid and hazardous waste. A brief history of the use of geotextiles within the Corps of Engineers is presented and an overview is given of the types of geotextiles available. The functions of geotextiles are described and specific applications of these and related products to solid waste disposal sites are suggested.

BACKGROUND

The use of synthetic fabrics in engineering construction works in the United States appears to have started in 1958 in Florida where a woven fabric was substituted for a graded filter blanket in the construction of shore protection. Throughout the 1960's, the U. S. Army Corps of Engineers (CE) used woven fabrics in increasing amounts, primarily in flood control levee slope protection systems and as natural filter material substitutes wrapped about perforated pipes in trench drain systems. The increasing usage of such products by CE Districts stimulated conduct of the research by Calhoun at the U. S. Army Engineer Waterways Experiment Station (WES), published in 1972, directed at developing design guidelines and CE acceptance criteria for use of woven fabrics in CE projects. Calhoun's work included the single nonwoven fabric on the market in the United States at that time (Phillips Petromat), but he did not attempt to establish criteria for nonwoven materials. In March 1972, the Office, Chief of Engineers (OCE) issued Civil Works Construction Guide Specification CE-1310, "Plastic Filter Cloth," which provided official guidance to CE Districts for acceptance of only woven-type fabrics. Subsequent to the guide specification issuance, however, the use of nonwoven fabrics in engineering construction increased dramatically. Consequently, WES was authorized to develop acceptance criteria for nonwoven fabrics. This work was incorporated into a new Civil Works Construction Guide Specification, CW-02215, "Plastic Filter Fabric," issued in October 1975 and revised in November 1977. The CE is currently using fabrics in a variety of applications including the lining of trench drains, retaining soil beneath riprap slope protection, wrapping perforated collector pipes, lining drainage blankets, reinforcing the foundations under dredge spoil dikes and a barrier to intrusion of pavement subgrade soils into base or subbase materials.

For the purpose of this paper, a geotextile is defined as any synthetic textile product that can be or is made to be incorporated in a civil engineering structure. In addition, plastic grids and strip drains incorporating geotextiles as an integral part of the product are included. In addition to the term "geotextile" the terms "filter fabric," "geotechnical fabric," and "engineering fabric" are in common use in the United States. The term "membrane" is used in Great Britain to refer both to geotextiles (permeable membranes) and to impermeable plastic films either with or without internal fiber reinforcement. "Geofabric" is sometimes also seen in the literature.

There has been a rapid growth in the literature on geotextiles in the last five years. Some major sources of information about geotextiles and their uses are:

a. Construction and Geotechnical Engineering Using Synthetic Fabrics, by Robert Koerner and Joseph P. Welsh, 1980.

b. Membranes in Ground Engineering, by P. R. Rankilor, 1981.

c. "Evaluation of Test Methods and Use Criteria for Geotextile Fabrics in Highway Applications," Federal Highway Administration Report No. FHWA/RD-80/021, 1980.

d. International Conference on Use of Fabrics in Geotechniques, Ecole Nationale des Ponts et Chaussees, Paris, 1977.

e. Proceedings, Second International Conference on Geotextiles, August 1-6, Las Vegas, Nev., Volumes I-III, Industrial Fabrics Association International, 1982.

Despite the rapidly expanding use of geotextiles, their use and performance in applications to solid and liquid waste disposal sites have gone essentially undocumented in the open literature.

PURPOSE AND SCOPE

The purpose of this paper is to present a general overview of the types of synthetic fabric products available for use in controlled sanitary landfill construction or in remedial measures for uncontrolled site cleanup. In addition, specific geotextile applications are suggested. The final report on this project will present additional details including design criteria for various applications and preferred construction practices. Therefore, the final report will serve as a handbook suitable for use in various waste management activities.

FABRIC TYPES AND CONSTRUCTION

Fabric Materials

Geotextiles are currently being made from polypropylene, polyester, polyethylene, nylon, polyvinylidene chloride, and fibreglass. Polypropylene and polyester are by far the most used of these materials. The physical properties of all these materials can be varied considerably, depending on the additives used in composition and on the methods of processing into filaments and subsequent incorporation in the finished fabric. The tensile strength of polyester and polypropylene filaments can be increased greatly by drawing or stretching the filaments while they are cooling from the molten state. The resistance to degradation from ultraviolet light varies among the polymers, but all can be made relatively resistant to deterioration by the incorporation of additives during manufacture.

The long-term durability in actual applications is not yet established for geotextiles, although resistance to many soil environments can be assumed from tests on the polymers when used in other applications, such as sheathing for buried cables, pipes, etc. The commonly used plastics seem to have considerable resistance to biological and chemical degradation in ordinary environments. However, the environment at solid waste landfills is potentially much more severe than the typical conditions to which geotextiles are exposed. In some applications, the fabric will be subject to contact with leachate from the fill or from volatile constituents that may have a deleterious effect on the fabric polymers or bonding resins. It is therefore necessary to consider the potential for chemical and biological deterioration when planning long-term application in solid waste fills.

Fabric Construction

The woven type of construction is the most expensive, but tends to produce fabrics with relatively high strengths and moduli (ratio of tensile stress to tensile strain) and relatively low elongations at rupture. The modulus, however, depends greatly on the orientation. When woven fabrics are pulled on a bias to the direction of the fibers, the modulus decreases dramatically, although the ultimate breaking strength may increase. Woven construction also produces fabrics with a relatively simple pore structure and narrow range of pore sizes or openings between fibers. Woven fabrics can be composed of monofilaments or multifilament yarns. The monofilament woven fabrics are generally used for filter and some reinforcement applications. The multifilament woven fabrics are usually restricted to reinforcement applications because these fabrics are expensive and have the highest strengths of all fabrics. A special type of monofilament is the slit film or ribbon filament fabric. The fibers for this fabric are thin and flat, rather than round or nearly round in cross section, and are made by cutting sheets of plastic into narrow strips. These fabrics are relatively inexpensive among the woven fabrics and are primarily used for separation, i.e., preventing the intermixing of two materials such as aggregate and fine-grained soil. Another special type of multifilament fabric is one made from slit (fibrillated) film filaments.

The knitting process is not widely used in the making of geotextiles. Only two fabrics are known to be made by this process; one is designed for unidirectional soil reinforcement and the other for surface erosion protection. With knitted fabrics, the strength properties can be varied unidirectionally or multidirectionally. The advantages of the knitting process are that it is less expensive than weaving and it is possible to knit tube shapes.

Nonwoven fabrics comprise those fabrics which are formed by some process other than weaving or knitting. These fabrics can be made from either continuous filaments or from staple fibers. In either case, the fibers are laid on a supporting screen or belt to form a mat and then bonded using one of the processes described below. The orientation of the fibers is usually more or less parallel with the plane of the fabric, but depending on the process, the fibers can be randomly oriented in the plane or can be given preferential orientation. In some processes, staple fibers can be given an orientation perpendicular to the plane of the fabric so that the fiber ends are exposed at the surface of the mats. In the spunbonding process, filaments are extruded, drawn to increase the polymer orientation, and hence strength, and laid on the moving belt or screen as continuous filaments to form the mat which is then bonded by any one of the processes described below.

a. Needle punching. Bonding by needle punching involves pushing many barbed needles through the fiber mat normal to the plane of the fabric. The process causes the fibers to be mechanically entangled. The resulting fabric has the appearance of a felt mat. The size of the needles determines the sizes of the largest openings in the fabric, but the complex structure of the matted filaments determines the overall permeability and pore characteristics. Needle-punched fabrics can be formed by needling a single mat thickness or by needling several mat thicknesses together.

b. Heat bonding. In this process the mat is laid and then the fibers are bonded at some or all of the points where fibers cross one another. This can be done by incorporating fibers of the same polymer type but having different melting points in the mat or by using heterofilaments, that is, fibers composed of one type of polymer on the inside and covered or sheathed with a polymer having a lower melting point. With heterofilament bonding, up to 100 percent of the fiber crossover points can be bonded, the number of bonds being controlled by the percentage of heterofilaments in the mat.

c. Resin bonding. Resin is introduced into the fiber mat, coating the fibers and bonding the contacts between fibers.

d. Combination bonding. Sometimes a combination of bonding techniques is used to facilitate manufacture or confer desired properties. Since needle punching tends to leave the fibers relatively free to move with respect to each other, heat or resin bonding can be combined with it to increase the dimensional stability of the fabric. Very open woven fabrics are also sometimes coated to fix filament positions.

Combination fabrics are fabrics which combine two or more of the fabrication techniques previously described. The most common combination fabric is a nonwoven mat that has been bonded by needle punching to a woven scrim. The nonwoven mat may be on one or both sides of the woven backing.

Special products are lumped under the general category of geotextiles but are either not properly called fabrics in the same context as used above or are secondary products which incorporate fabrics. Some of these are described below.

a. Grids or meshes. Included here are the heavy construction grids or meshes of polyethelene used mostly in soil reinforcement applications. Some of these are drawn during manufacture to orient the molecular structure to provide excellent tensile strength. Another product is a thick, open mat composed of crimped and tangled monofilament fibers, heat-bonded at the contacts to form a three-dimensional net particularly suited for erosion control. These first two products are also being sandwiched between nonwoven fabrics to create self-contained subsurface drainage layers. Another special product suited for surface erosion control, particularly during establishment of vegetative cover, is a polypropylene open-knitted netting interlaced with strips of paper. Still another newer product is formed as a mat of very strong composite webbing or polyesther filaments sheathed in polyethylene.

b. Strip drains. An expanding use of fabrics is in the construction of strip drains heretofore primarily used as vertical drains to accelerate the consolidation of soft soils. Typically, the strip drains are inserted into the soil using special equipment. Several commercial sources are available in the United States and Canada for this technique. The actual details of fabrication of strip drains vary slightly from one manufacturer to another, but nearly all drains consist of a continuous channeled plastic core, 9 cm (3.5 in.) to 10 cm (4 in.) wide, surrounded by a fabric or occasionally a heavy paper envelope. The plastic core holds the envelope open while the channels in it provide a conduit for the movement of fluid out of the soil. Strip drains are produced in continuous rolls up to 140 m (450 ft) in length. In the typical installation as vertical drains to accelerate consolidation as part of a preload fill technique, the strip drain roll is mounted on the specialized insertion equipment much like a spool of thread on a sewing machine and the drain is "stitched" within a mandrel into the soft soil to the required depth. The drain is then cut off a foot or so above the ground surface after the mandrel is withdrawn and the insertion machine is moved to the next locaton to repeat the operation. Such a procedure permits economical placement of a large number of drains over an area at close spacing (generally 0.9-m (3-ft) to 1.8-m (6-ft) grid on centers). After all drains are in place over the specified construction site area, a layer of pervious soil (sand) is placed around and over the protruding drain ends. The area is then covered with a sufficient thickness of additional random fill to somewhat exceed stresses expected to be imposed by the structure to be built. After consolidation (settlement) of the soft soil is sufficiently complete, the surcharge fill is removed, and select compacted fill placed, if required, to bring the site to grade.

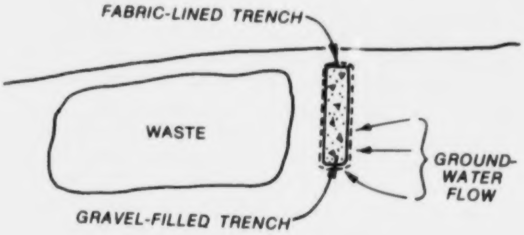
c. Coated fabrics. The foregoing discussion has dealt only with products which can be classified as permeable to liquids and gases. Fabrics are, however, used extensively as reinforcement for impermeable synthetic membranes. These membranes have been used as liners for water, wastewater, and other liquid/slurry lagoons. These membranes also have applicaton in the capping/covering of solid waste disposal sites, but heretofore their higher cost has discouraged their general use. However, several less expensive products have come on the market recently which can be considered as hybrids between fabrics and membranes. These differ from conventional reinforced membranes in that an impermeable film of either ethylene vinyl acetate or polyethylene is bonded to one side of a nonwoven fabric partially penetrating the fabric thickness. Because the bonding systems are only partially penetrating and as yet unproven, these materials may not be suitable for liquid containment, but they could function well as water shedding elements in a cap/cover design. Certainly, they may offer greater strength and puncture resistance than the unreinforced membranes now most widely used.

SOME SUGGESTED USES OF GEOTEXTILES FOR LAND WASTE DISPOSAL SITES

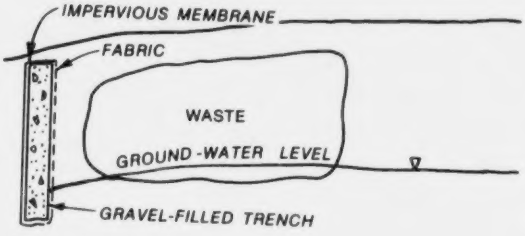
Filtration

This is probably the most commonly employed function of both woven and nonwoven fabrics. The fabric must meet the basic criteria required of natural graded filters, i.e., those of stability and permeability. To meet stability requirements, the fabric opening sizes must be such that particles of the soil being retained or filtered will not pass through. The permeability criterion which must be satisfied concurrently with that of stability is that the fabric must also be capable of freely draining the soil retained.

Subsurface interceptor drains may be utilized upslope from waste fills to intercept and divert groundwater from entering the waste and becoming contaminated or, in some cases, they may have application downslope from a waste site to intercept contaminated groundwater for controlled removal and treatment. These two applications are shown in Figure 1. Filter fabrics may be placed between the in situ soil and the pervious trench backfill soil to prevent movement of the in situ soil into the trench while permitting the free flow of fluid. Perforated collector pipes are utilized near the bottom of the trench to facilitate removal of fluid. If the most economical pervious trench backfill material is sufficiently fine in gradation such that it would enter the collector pipe openings, the pipe can be wrapped with filter fabric to prevent that intrusion.



a. Upslope interceptor drain



b. Downslope effluent interceptor drain

Figure 1. Subsurface interceptor drains using fabrics.

The filtration functions for subsurface drainage blanket systems are the same as for trench drains described above except orientation is essentially horizontal. The purpose of the blanket is to drain fluid from overlying material or to prevent the rise of fluid from below into an overlying material.

The filtration of fabrics used in surface drainage ditch lining applications is most needed for cover soils which are finer grained cohesionless sands or silts. The fabric is used to line the ditch and rock or gravel is placed upon the fabric to secure it in place, to shield the fabric from ultraviolet light, and to dissipate the energy of the flowing water. The sizing of the rock or gravel and the ditch dimensions are, of course, based on anticipated flow velocities and quantities. This application, as shown in Figure 2, was used successfully at the Windham, Connecticut, municipal waste landfill site where the cover soils of cobble, gravel, and sand mixtures were suffering erosion along concentrated runoff paths which had exposed the cap membrane in several places. The fabric in this application does aid in erosion control but by means of its filtration action preventing cover soil particles from being moved into and through the open work rock or gravel above.

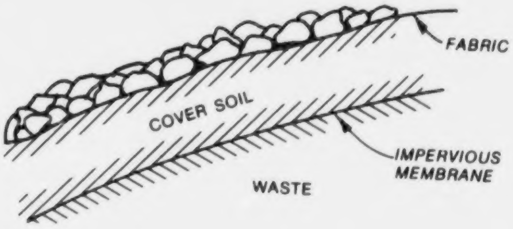


Figure 2. Permanent slope protection using fabric beneath rock.

Drainage

The filtration functions described above are in association with drainage functions. For applications described here, the fabric or combination fabric-grid-net product not only performs filtration, but also serves as a conduit for fluid being drained. Thick, needle-punched nonwoven and combination fabrics or special products specifically designed for this purpose are most commonly used.

Figure 3 illustrates the use of trench drains and blanket drains as a substitute for backfilled trenches as previously shown in Figure 1. Drainage blanket use is shown in Figure 4. It is particularly noted that strip drains offer an excellent and less expensive alternative to the use of perforated pipe as collectors within a cover drainage blanket or a pond underdrain system. In any of these uses, care must be taken in selecting the fabric, combination, or special product to be sure that it can carry the required discharge and that any anticipated stresses will not compress the product sufficiently to destroy its drainage capability.

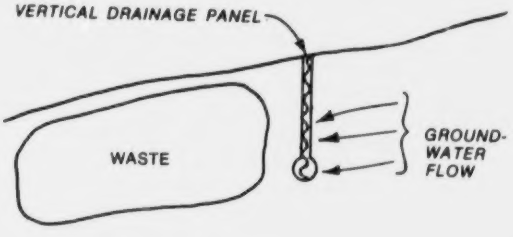


Figure 3. Upslope drainage trench.

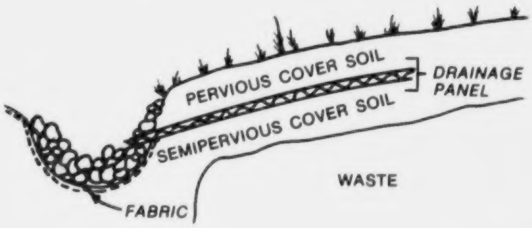
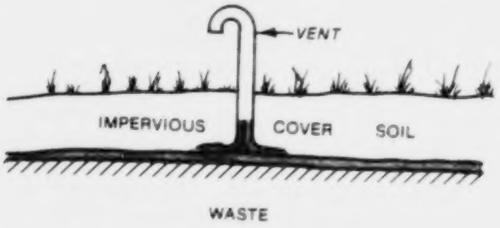


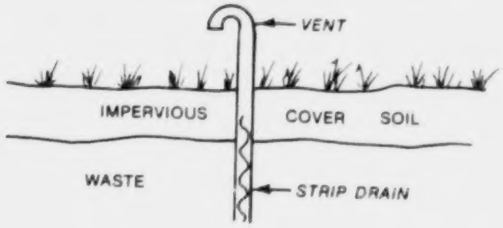
Figure 4. Fabric drainage layer.

Venting

The most common use of fabric for gas venting to date has been to underlay a synthetic membrane liner for a liquid storage facility. In some cases, organic matter is present beneath the linings of these reservoirs. As the organic matter decays, methane gas is released and, if it has no way to escape, can cause the liner membrane to balloon up through the reservoir liquid. A fabric installed between the liner and soil provides an avenue for the release of these gases. Fabric can be given a similar use in conjunction with covering a waste site. A fabric having good permeability in the plane of the fabric could be placed over the waste but beneath the cover soil or membrane and would provide a conduit for waste-generated gases. At intervals, a riser pipe could be installed to release the gas as it collected in the fabric. An alternative design would incorporate fabric strip drains to replace the perforated pipe now used in vertical gas collector pipes. Figure 5 shows these applications.



a. Gas vent using fabric layer under cover soil



b. Gas vent using strip drain

Figure 5. Gas venting using geotextiles.

In some cases it is necessary to intercept gas as it migrates horizontally from a site. In these cases, trenches lined with fabric and filled with gravel could act as gas interceptors similar in construction to the types of trenches used to intercept and drain water flows except that standpipes would lead from the trenches to dissipate accumulated gas.

Reinforcement

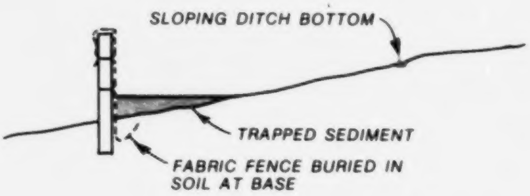
Geotextiles can be used in various applications where reinforcement or support is needed. A fabric can be placed beneath an impermeable synthetic membrane to act as a cushioning and load distribution layer to reduce the incidence of puncturing. This fabric could help prevent excessive deformations and rupture of the membrane as the fill settled unevenly or as cracks formed in the fill beneath the membrane.

Allied with this application is the application where fabric is placed over an impermeable membrane to protect it from damage during construction operations. The fabric may also reduce the possibility of cover soil sliding from the sloping surface of the cover membrane and exposing the membrane to sunlight damage or damage from other causes. The fabric would in this case be reinforcing the soil cover by increasing shear resistance between soil and membrane. A fabric placed over a sloping membrane cover could prevent cover soil from sliding off a membrane as slope angle increased during fill settlement. This would also permit the protection of steeper slopes using a synthetic membrane than is presently possible. Fabrics may also be used for reinforcement by embedding a fabric or special plastic grid in the cover soil. This would act as a tension member and reduce or prevent cracking of the cover soil caused by uneven settlement or localized surficial sliding of cover soil on the steeper slopes.

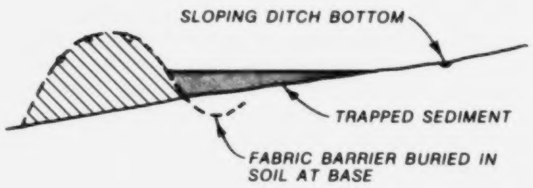
Erosion Control

Geotextiles may be used for erosion control in temporary or permanent applications. In one temporary application the fabric is used to prevent sheet erosion in newly seeded slopes. A fabric specially designed for this application is anchored on a prepared and seeded slope and holds soil in place until seeds germinate and vegetative cover is established. Fabrics used for this purpose are designed to disintegrate after the vegetation has had time to establish itself.

In other temporary erosion control applications, fabrics are used in the construction of silt fences and brush barriers. The purpose of these temporary structures is to reduce the amount of soil loss from a construction site due to surface erosion in storm runoff. The silt fence or brush barrier serves to reduce the velocity of the running water to allow suspended solids to settle out of suspension and also to provide a physical filtering action to remove suspended particles. Figure 6 shows these applications. Sediment will eventually build up behind the barrier and additional barriers can be built atop the accumulated sediment. Since these barriers are temporary, the accumulated sediment is usually regraded and stabilized by vegetation or by other means after construction is complete. Silt fences or brush barriers are not usually used where runoff volumes are large.



a. Silt fence



b. Brush barrier

Figure 6. Temporary erosion control measures.

Geotextiles are frequently used for permanent erosion control applications. In the most common of these applications, fabric is used beneath a riprap, gravel, concrete blocks, or gabions to prevent the loss of finer soil from a slope surface while also serving the filtering drainage function of allowing relief of hydrostatic pressures from within the slope. Frequently, a layer of gravel or crushed stone is placed between the fabric and the stone to protect it from damage during placing of the cover stone and to minimize exposure to sunlight and other environmental degradation. A geotextile is often used in areas of concentrated water flow such as culvert outlets and swales where the fabric is usually staked in place or covered with a layer of gravel or stone.

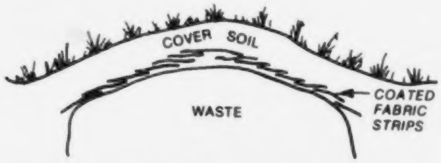
The same approach can be applied in solid waste cover soils. Here, the fabric would serve to hold the fine-grained cover soil in place while the gravel would act to protect the fabric from environmental exposure.

Fabric is also used between a rock buttress or gabion and soil slope to allow dissipation of hydrostatic pressure while preventing soil from sloughing into and eventually washing through the buttress stone.

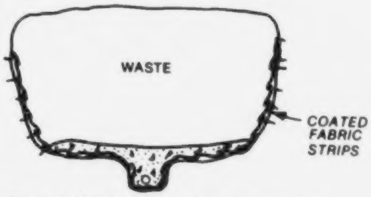
Separation

A fabric can be used to keep two materials separate. In construction of expedient roads over soft soils, for example, fabric is often placed over the soft subgrade soil and gravel or crushed stone pushed onto the fabric. With sufficient thickness, the gravel or crushed stone provides a stable base for vehicular traffic. In the separation application, the ability of the fabric to pass water is usually of secondary importance and may not be necessary at all. In the capping of waste lagoons or areas where mucky waste must be covered, a fabric may be rolled out onto the surface of the waste and covered with soil or aggregate. This would provide a firm working surface on which to place the capping layers of either synthetic membrane or soil. In such applications, some benefit is derived from the ability of the fabric to strengthen the cover system. The mechanism by which this is done is not well understood, but it is believed that fabric is put in tension by the deforming or rutting of the soil beneath and this allows tensile load to be taken by the fabric.

A special case of separation is the application of coated fabrics used as water barriers or shingling for the cover of a solid waste site as shown in Figure 7. In the applications shown, it is not necessary that seams between the fabric panels be sealed if the cover is designed to eliminate pooling of water.



a. Coated fabric as cover shingling



b. Coated fabric as used in fill interior drainage system

Figure 7. Use of coated fabrics for prevention of effluent migration.

SUMMARY

The use of geotextiles in waste management facilities has yet to reach its full potential. Additional research will have to be performed before these materials are accepted and used. Techniques will have to be developed and evaluated to provide design criteria for the user community. Work is underway which will provide this data but in the meantime geotextiles deserve consideration in the design, construction, maintenance, and closure of land disposal facilities.

POTENTIAL MECHANISMS AND REMEDIES FOR CLOGGING OF LEACHATE DRAIN SYSTEMS

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ABSTRACT

Preliminary results are presented from a study of the potential for clogging of leachate collection systems and possible preventative and mitigative remedies. Some important mechanisms for clogging are iron deposition, calcium carbonate incrustation, formation of biological slimes, and various physical mechanisms. Preliminary results of a laboratory analysis of a sample of partially cemented pea-gravel from the leachate collection system in Boone County Field Site (Test Cell #1) indicate iron, silica (quartz), calcium and magnesium as the primary constituents in the cement. The remainder of the study will address the reason for the clogging at Test Cell #1, the potential for clogging of leachate collection systems at existing facilities, the expected effectiveness of preventative and mitigative remedies to clogging, and recommendations for further research.

INTRODUCTION

Current EPA Permitting Standards for hazardous waste disposal facilities (40CFR 264), promulgated 26 July, 1982, contain the following requirements for leachate collection and removal systems in single and double-lined waste piles and landfills (264.251(a)(2), 264.301(a)(2)):

- leachate depth over the liner must not exceed 30 cm (1 ft);
- a leachate collection and removal system immediately above the liner must be designed, constructed, maintained, and operated to collect and remove leachate;
- construction materials must be chemically resistant to the waste managed and leachate expected to be generated, and must be of sufficient strength and thickness to prevent collapse under expected loading; and
- the system must be designed and operated to function without clogging through the scheduled closure of the landfill.

In addition, Part 264.303(b)(4) requires that while in operation a facility "must be inspected weekly and after storms to detect evidence of... the presence of leachate in and proper functioning of leachate collection and removal systems, where present."

To assume safe and legal operations at hazardous waste landfills and waste-piles, therefore, leachate collection systems must maintain flow capacity over the expected life and closure of the facility. Little is known, however, about the potential for failure of these systems. Experience in the related field of agricultural drainage systems indicates that the service life of such drains is rather short; repairs are expected to be required after about twelve years of use (1). A recent study of 18 leachate collection systems found that 17% had known problems with clogging. However, it was also found that most operators assumed that as long as leachate was being collected, the system was functioning properly. In many cases, leachate depths were not even monitored (1). Since failure of the leachate collection system can be defined as a leachate buildup on the liner exceeding 30 cm in depth, many operators would not know if failure had occurred.

It is the responsibility of the Regional Administrator in permitting a facility to specify design and operation conditions to ensure that the leachate depth over the liner does not exceed the 30 cm limit. Estimates of the potential for clogging of leachate collection and removal systems and means to reduce that potential through better design or through in-place remedial techniques are therefore needed.

OBJECTIVE AND APPROACH

The objective of this project was to aid RCRA personnel in determining whether or not current design requirements for leachate collection and removal systems are adequate. The emphasis was to develop a basis for estimating the potential for drain clogging at hazardous waste disposal facilities and determine a set of practical preventive and mitigative remedies.

To accomplish this, information was collected from three basic areas. First, the available literature on clogging mechanisms and drain systems was reviewed. This included a limited number of primary sources on leachate collection system design and clogging, and sources from related areas such as agricultural drainage and septic system maintenance. In addition, available information on leachate collection at existing municipal and hazardous waste landfills, including leachate characteristics was collected. Second, a cemented sample of pea gravel from the drainage envelope at the EPA test landfill in Boone County, KY was analyzed to determine the character and mechanism of the cementation. The results of this analysis are discussed below. Finally, original data was collected to determine current experience with leachate collection systems and to estimate the potential for clogging of existing drain systems and the effectiveness of proposed remedies.

At the time this paper was written, much of the literature review and a preliminary analysis of the cemented gravel sample had been completed. Some of the important preliminary results are presented below.

CLOGGING MECHANISMS

Clogging mechanisms can be defined as the occurrences or natural processes which inhibit the flow of leachate to or through the leachate collection system. As stated above, a system is considered to be clogged if the leachate depth over the liner exceeds 30 cm. Some important clogging mechanisms, as determined by a recent EPA study of clogging in leachate collection systems (1) are:

- calcium carbonate incrustation;
- iron deposition;
- formation of biological slimes; and
- physical mechanisms.

Calcium carbonate ($CaCO_3$) incrustation occurs by a mechanism similar to that seen in the natural formation of stalactites. When a solution containing appreciable concentrations of calcium and bicarbonate ions is subjected to a decrease in pressure (or in partial pressure of carbon dioxide [P_{CO2}] in equilibrium with heat solution) then the bicarbonate equilibria ($2HCO_3^- \rightleftharpoons CO_2 + CO_3^= + H_2O$) will favor release of CO_2 and formation of carbonate ions. These carbonate ions combine with calcium ions (Ca+2) to form a $CaCO_3$ precipitate once the $CaCO_3$ solubility product is exceeded. This precipitate can build up on the collection pipe or cause cementation of the surrounding drain envelope.

The potential for $CaCO_3$ incrustation is primarily a function of:

- total or bicarbonate alkalinity;
- calcium hardness;
- concentration of bicarbonate and calcium ions in relation to the solubility of $CaCo_3$;

- pH; and
- changes in pressure or partial pressure of CO_2.

Iron deposition can occur from a number of complex processes involving either Fe(II), Fe(III) or both oxidation states. Important types of iron deposits include ochre (a general term for precipitates of iron, including $Fe(OH)_3$), iron sulfide (FeS), and various colloidal complexes. Factors which influence iron deposition of ochre and sulfide are given in Table 1. The presence of various complexing agents complicate the formation of iron deposits. Soluble complexing agents (e.g., Cl^-, Br^-, F^-, CN^-, I^-) tend to keep iron species in solution, thereby reducing their availability for the iron deposition processes. Alternatively, some organic complexing agents (e.g., tannins, humic acids, and aromatic hydroxyl compounds such as phenols) may form colloidal iron complexes in water. These would act as sites for the accumulation of ferric (Fe^{+3}) compounds and subsequent trapping of particulate matter (1). Iron deposits can restrict leachate flow by clogging the inside of pipes or causing cementation or clogging of the materials surrounding the pipes (2).

TABLE 1.

FACTORS CONTRIBUTING TO IRON DEPOSITION

Factors	Ochre	FeS
pH	7.4 - 9.5	4-8
redox potential	-10 ± 20 mV	<0 mV
temperature	20 - 30°C	20 - 40°C
Fe $^{+2}$ concentration	.2 - .5 mg/l	favorable
bacteria required	iron-reducing	sulfate-reducing
aerobic conditions	favorable	unfavorable
total sulfides	-	>2 ppm
organic materials	favorable	unfavorable
soil type	organic - favorable silt and clay loams--unfavorable	

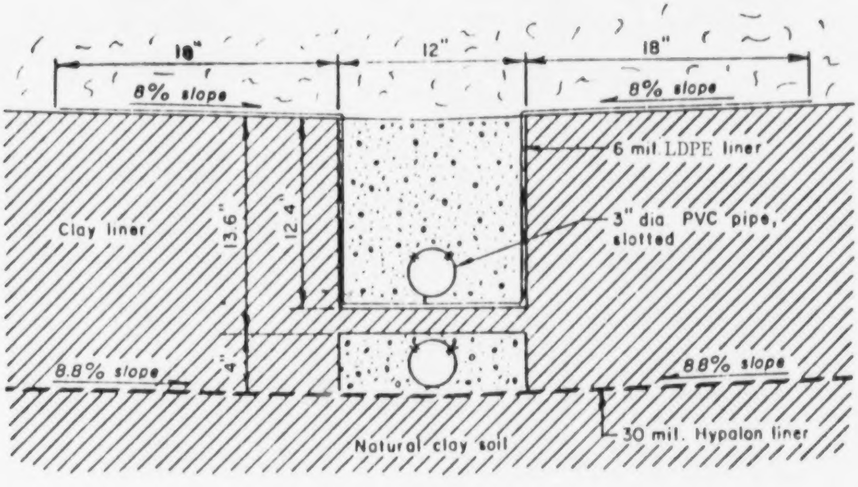
The formation of biological slimes can occur when slime-producing bacteria or organisms are present under favorable conditions. In general, the formation of biological slimes is dependent on the presence of bacteria together with the appropriate nutrients, growth conditions and energy sources.

In particular, Vitreoscilla, a filamentous slime forming organism, and Pseudomonas, a common soil bacteria, are known clogging agents when iron is not present. Enterobacter is also known to contribute to the clogging of the area abutting drain envelopes (1). Studies of the biological clogging of sand (3,4) indicate that the following factors are thought to contribute to biological clogging:

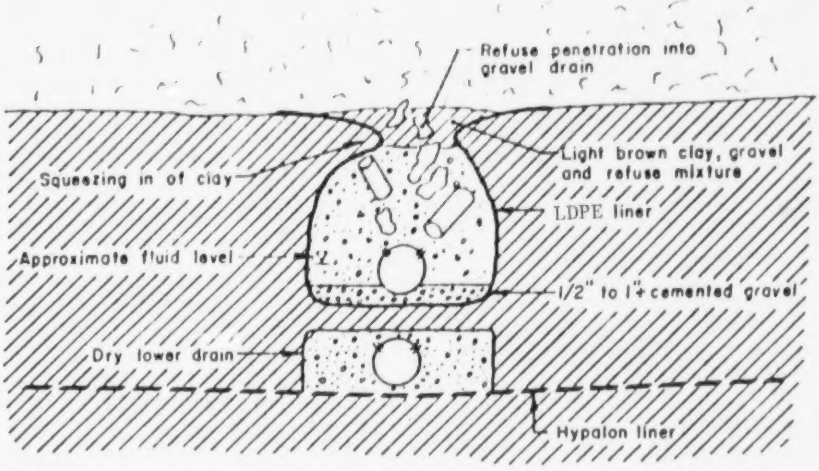
- carbon to nitrogen ratio in the leachate;
- rate of nutrient supply;
- concentration of the slime materials (polyuronides);
- temperature; and
- soil moisture.

Physical mechanisms which clog leachate collection systems include pipe collapse due to loading, hydraulic removal of fines in the soil (scouring or piping) surrounding the drain envelope, deterioration of the pipe material, and deposition of suspended solids. The principle factors which contribute to physical clogging are:

- soil grain size;
- leachate characteristics
  - production rate
  - volume
  - head
  - velocity;
- pipe characteristics
  - size
  - material;
- design of joints, outlets, envelope, filter;
- pipe placement, depth and loading;
- depth to watertable; and
- maintenance and inspection.


18"
12"
18"
8% slope
8% slope
6 mil LDPE liner
Clay liner
13.6"
12.4"
3" dia PVC pipe, slotted
4"
8.8% slope
8.8% slope
Natural clay soil
30 mil. Hypalon liner

(a) As-built Construction Details
Cross section at observation bulkhead


Refuse penetration into gravel drain
Light brown clay, gravel and refuse mixture
Squeezing in of clay
LDPE liner
Approximate fluid level
1/2" to 1"+ cemented gravel
Dry lower drain
Hypalon liner

(b) Cross section as exposed
8 feet from observation bulkhead

FIGURE 1. LEACHATE COLLECTION SYSTEM, Test Cell #1 (Ref. 5)

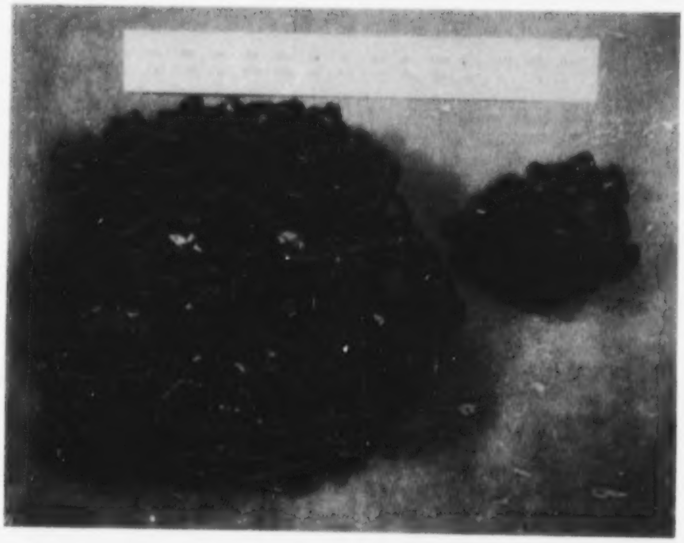


FIGURE 2. Cemented Mass of Pea Stone

PRELIMINARY CHARACTERIZATION OF A CEMENTED DRAIN SECTION

INTRODUCTION AND APPROACH

When Test Cell #1 of the Boone County Field Site was dismantled in September, 1980 after nine years of testing, a section of partially cemented gravel was discovered in the drain envelope extending from 6.5 to 13.5 feet from the collection sump (bulkhead). Cross-sections of the Test Cell as constructed and as exposed are given in Figure 1. The discovery of the cemented section was significant because the Test Cell, along with four others, was constructed to provide a better understanding of the processes and related environmental effects that occur in sanitary landfills (5). It is therefore important to determine whether the causes of cementation are unique to the condition at the small-scale test landfill, or whether they are common to sanitary and hazardous waste disposal landfills in general.

The gravel sample consisted of a small amount of loose, rounded pea-stone plus two or three large masses of similar stones firmly held at contact points between the stones by a thin layer of red-brown cement. The largest of these cemented aggregates was a flat, disc shaped mass approximately 12 cm across and 5 cm in thickness. It appeared to be graded or classified with large, individual stones of 1 to 2 cm diameter on one side, and smaller stones of 0.5 to 1.0 cm on the other. A photograph of the two larger masses of material is shown in Figure 2.

Two approaches were used in the initial analysis of the gravel sample. The first involved a physical analysis of the cement material itself, including scanning electron microscopy, optical microscopy, and x-ray diffraction and fluorescence analysis. The second involved a more general chemical analysis of the mass to determine the primary chemical constituents in the cemented sample.

The results of these microscopic studies lead to the preliminary conclusion that the cementing agent for the small stones is likely a co-precipitated mixture of calcium carbonate and an insoluble iron hydroxide. This combination, along with the silica, constitutes the principal components of the cement. However, aside from a few isolated crystals, calcium carbonate is not observed microscopically as a separate phase and is not present in the x-ray diffraction pattern. Since the calcium is present in a substantial quantity, if it were present as pure calcium carbonate we would expect to detect the crystalline form (either calcite or aragonite) by this technique. This ambiguity suggests that the calcium and iron may well have co-precipitated in an amorphous form and, as such, are not "seen" by x-ray diffraction.

RESULTS OF CHEMICAL ANALYSIS

In a preliminary test it was determined that dilute hydrochloric acid would not affect the gravel but would solubilize the material holding it together. To determine the composition of the cemented gravel material, a portion of the sample was treated with a known excess of acid and separated into acid-soluble and insoluble fractions. The soluble fraction was subjected to qualitative emission spectrographic analysis to identify the principal metal species which were then quantified by emission spectrometry. The insolubles were separated into size fractions and weighed.

A known weight (100 grams) of the cemented gravel was treated with a known amount of standardized hydrochloric acid and boiled for thirty minutes to effect complete dissolution of the cement material and to drive off the carbon dioxide formed. The insolubles were separated by decantation and filtration, dried, sieve-sized and weighed.

A portion of the filtered solution was analyzed for residual acidity by pH titration (to pH 5.0) using standardized sodium hydroxide solution, to measure the alkali content (acid consumption) of the dissolved material.

RESULTS OF PHYSICAL ANALYSIS

The microstructure of the cemented material as seen by the scanning electron microscope (SEM) is shown in Figure 3. Accompanying the SEM micrograph in Figure 3 is the spectrum of elements detected by the energy dispersive x-ray analysis system (EDS) attached to the SEM. EDS analysis of the cement material from various points on the sample indicated calcium and iron as the principal elements present. (Elements lighter than sodium are not detected). In addition, in the sample shown in Figure 3, a trace amount of manganese was detected.

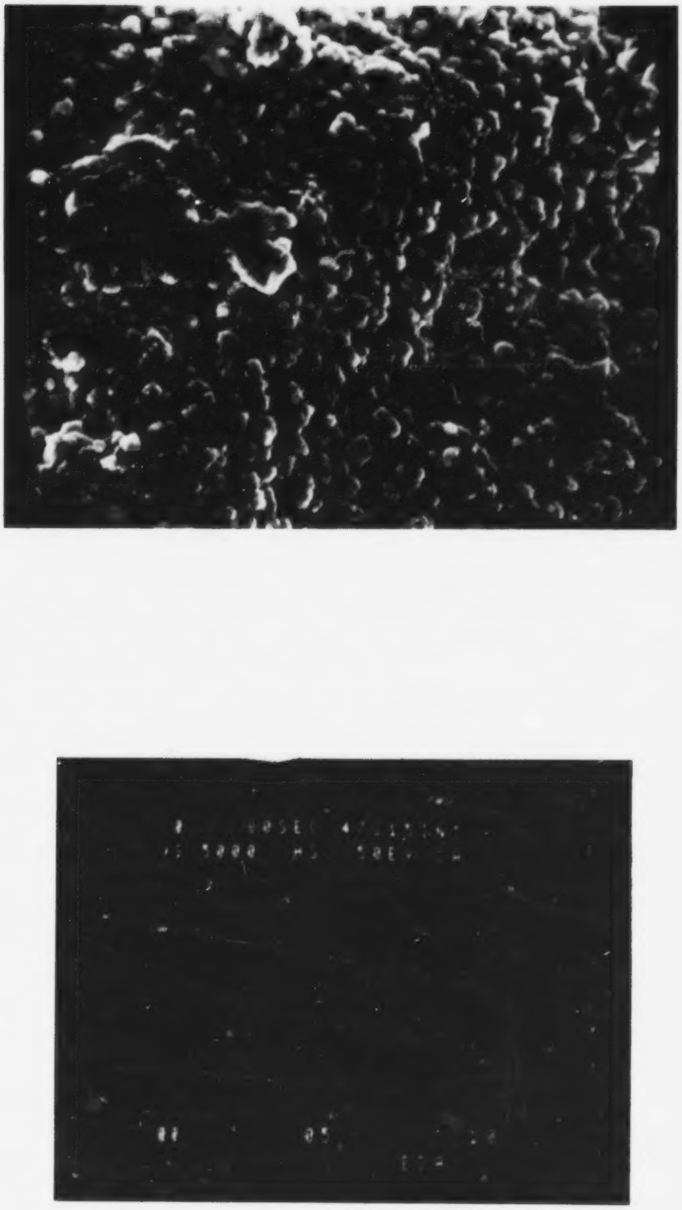
A larger amount of the red cement was isolated for analysis of the crystalline content by x-ray diffraction and elemental analysis by x-ray fluorescence. X-ray diffraction indicated silica (quartz) as the only crystalline material present.

X-ray fluoresence, which detects the presence of elements heavier than aluminum in atomic number, indicated a relatively very strong signal for calcium and iron, a weak signal for phosphorous, zinc, sulphur and silica, and a very weak signal for manganese and potasium.

Using optical microscopy under the petrographic (polarizing) microscope the reddish cement was observed to consist of three major constituents:

- silica;
- a colorless, apparently crystalline phase with calcium carbonate present; and
- an as yet unidentified phase consisting of an aggregated cluster of small red particals comingled with colorless crystalline particles of similar size range. The unidentified aggregates reacted vigorously with dilute acid, evolving large volumes of gas and leaving opaque red particles without the comingled crystalline phase.

The elemental composition of the major constituents in the cemented layer was determined by atomic emission spectroscopy. An emission spectrum was obtained using a Spectrospan III Direct Current Argon Plasma Optical Emission Spectrophotometer for qualitative analysis. This revealed Ca, Fe, Mg, and P as major constituents in solution, and Mn, Cr, Na, Ba, Si, Cu, and Sr present at lower levels. The major constituents, along with Mn, were quantified on Spectrospan III Spectrometer using the method of standard additions for each element analyzed. The results of these analyses are shown in Table 2.



Ca Mn Fe

FIGURE 3. Red Cement Microstructure with Trace of Manganese in EDS Spectra

TABLE 2

RESULTS OF CHEMICAL ANALYSES OF CEMENTED MATERIAL

Weight sample taken = 100.468 g
Weight insolubles remaing = 96.958 g
Apparent sample dissolved = 3.530 g

Alkalinity (acid consumption) in dissolved material = 60.3 mili equivalent

Elemental composition of dissolved material

Element	Weight Found
Ca	0.851 g
Fe	0.551 g
Mg	0.103 g
Mn	0.020 g
P	0.240 g

Size distribution of insolubles

Size	Weight Found
>2.0 millimeters (#10 Sieve)	94.015 g
<2.0 mm, >0.84 mm (through #10, on #20)	0.640 g
<0.84 mm, >0.25 mm (through #20, on #60)	0.933 g
<0.25 mm (through #60)	1.070 g

PRELIMINARY FINDINGS

The chemical and physical analysis data are being evaluated currently, and thus the findings at this point must be regarded as preliminary.

The "cement" is principally a calcium-iron-magnesium product containing significant proportions of carbonate (gas evolution) and phosphate. In addition, a relatively large proportion of fine silica appears to be dispersed in the cement.

The lack of significant x-ray diffraction patterns suggests that the cement is an amorphous material rather than composed of discrete crystalline phases. While little can be said yet about the clogging mechanism(s) at work here, carbonate incrustation is likely to have contributed. The role of iron is not yet clear - it may have been an active agent in precipitate formation, or may only be present as discrete oxide (red, Fe_2O_3?) particles which have been carried along.

Some additional work on chemical and physical characterization is planned with particular emphasis on elucidating the role of the fine silica particulate and the distribution and role of iron within the mixture. In addition, limited tests for the presence and distribution of organic materials are planned.

CONCLUSION

A number of the most important questions in the study remained to be answered when the paper was written, including:

- Why did the cementation occur in a localized section of drain envelope at Test Cell #1?
- Based on typical conditions and operating practices, is a similar or other form of clogging expected to occur at existing sanitary landfills or hazardous waste disposal facilities?
- What remedial measures will be effective in correcting expected clogging problems?
- What further research is necessary in this area?

These questions will be addressed based on analysis of theoretical clogging mechanisms, the actual clogging mechanism(s) at Test Cell #1, and further laboratory analysis and literature review. Final results will be presented at the 1983 Research Symposium and will be available in a published final report.

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ANALYSIS AND FINGERPRINTING OF UNEXPOSED AND EXPOSED POLYMERIC MEMBRANE LINERS

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ABSTRACT

A plan is presented for analyzing polymeric membrane liners for waste storage and disposal impoundments before and after laboratory or pilot-scale exposure and field service. These analyses can be used to fingerprint a material and to follow the changes that take place in a polymeric membrane liner during exposure to waste. They can also be used to determine components of a waste liquid that are absorbed and are aggressive to polymeric liners.

This analysis plan includes determination of volatiles, extractables, specific gravity, ash and crystallinity of polymeric liners. The plan also includes gas chromatography and infrared analysis of the extractables (and possibly of the organic volatiles) and thermogravimetric analysis of the liner. Also suggested is the use of pyrolysis gas chromatography, which can be performed directly on unexposed and exposed liner materials. Typical analytical results for unexposed and exposed liners are presented.

INTRODUCTION

Because of the wide range of compositions and constructions of flexible polymeric membrane liners that are currently available and being developed for lining waste impoundments, analysis and fingerprinting of the membranes is needed for a number of purposes. For example, a liner manufacturer needs to test his sheeting as new polymers are used and as new compounds and constructions are developed. He also needs tests to control the composition of the liner being manufactured.

The analysis of a polymeric membrane liner at the time of placement can be used for three purposes: first, as a means of characterizing and identifying the specific sheeting; second, as a baseline for monitoring the effects of exposure on the liner; and third, to assess the aggresive ingredients in the waste liquid to determine chemical compatibility.

During exposure to waste liquids, polymeric liners may change in composition in various ways that may affect their performance and result in actual failures. Polymeric materials may absorb water, organic solvents and chemicals, organometallic materials, and possibly some inorganics if the liners become highly swollen. On the other hand, the extractable materials in the original liner compound may be leached out and result in stiffening and even brittleness on the part of the liner membrane. The solid constituents of a polymeric compound (which include carbon black, inorganic fillers, and some of the curing agents) will be retained in the liner compound, as will the polymer of which the liner is made (particularly if the polymer is crosslinked). If organic materials are similar to the liner in solubility and hydrogen bonding characteristics, the liner may swell excessively. Some thermoplastic lining materials may even dissolve, when in contact with some solvents.

The objective of this paper is to present an analytical methodology that can be used to fingerprint and identify liner materials and to give a baseline for assessing the changes in composition of these materials when they are under test or in service. Also presented are the analytical procedures for testing exposed liner materials to determine these changes. Data on representative liner materials, before and after waste exposure, are presented.

POLYMERS USED IN MEMBRANE LINER MANUFACTURE

Polymers used in the manufacture of lining materials include rubbers and plastics differing in polarity, chemical resistance, basic composition, etc., and can be classified into four types:

- Rubbers (elastomers) that are generally crosslinked (vulcanized),
- Plastics that are generally unvulcanized (such as PVC),
- Plastics that have a relatively high crystalline content (such as the polyolefins), and
- Thermoplastic elastomers that do not need to be vulcanized.

Table 1 lists the various types of polymers that are used and indicates whether they are used in vulcanized or nonvulcanized form and whether they are reinforced with fabric. The polymeric materials most frequently used in liners are polyvinyl chloride (PVC), chlorosulfonated polyethylene (CSPE), chlorinated polyethylene (CPE), butyl rubber (IIR), ethylene propylene rubber (EPDM), neoprene (CR), and high-density polyethylene (HDPE). The thickness of polymeric membranes for liners ranges from 20 to 120 mils, with most in the 20 to 60-mil range.

TABLE 1.POLYMERIC MATERIALS USED IN LINERS

Polymer	Use in liners: Thermoplastic	Use in liners: Vulcanized	Fabric reinforcement: With	Fabric reinforcement: W/O
Butyl rubber	No	Yes	Yes	Yes
Chlorinated polyethylene	Yes	Yes	Yes	Yes
Chlorosulfonated polyethylene	Yes	Yes	Yes	Yes
Elasticized polyolefin (partially crystalline)	Yes	No	No	Yes
Elasticized polyvinyl chloride	Yes	No	Yes	No
Epichlorohydrin rubber	Yes	Yes	Yes	Yes
Ethylene propylene rubber	Yes	Yes	Yes	Yes
Neoprene (chloroprene rubber)	No	Yes	Yes	Yes
Nitrile rubber	Yes	---	Yes	---
Polyethylene (partially crystalline)	Yes	No	No	Yes
Polyvinyl chloride	Yes	No	Yes	Yes

Most polymeric lining materials are based on single polymers, but blends of two or more polymers (e.g., plastic-rubber alloys) are being developed and used in liners. Consequently, it is difficult to make generic classifications based on individual polymers in the liners, even though one polymer may predominate. Blending of polymers introduces the long-range possibility of the need for performance specifications, but long-term liner performance in the field cannot presently be completely defined by current laboratory tests.

The basic compositions of the different types of compounds are shown in Table 2. The crosslinked rubber compositions are usually the most complex because they contain a crosslinking system that requires more ingredients (e.g., the sulfur system). Thermoplastics, except for CSPE compounds, contain no curatives. Although supplied as thermoplastic membranes, CSPE liners contain inorganic crosslinking chemicals that allow the compound to crosslink slowly over time during service. Crystalline materials have the simplest composition and generally consist of polymer, a small amount of carbon black for ultra-violet protection, and antidegradants.

Of the various liner components (except for the polymer), the following are potential extractables:

- Small amounts in the original polymer (i.e., stabilizers and antidegradants)
- Oils and plasticizers
- Antidegradants added to the compound.
- Organic constituents of the sulfur crosslinking system (e.g., vulcanization accelerators and activators).

These ingredients are extracted in the determination of extractables.

Most of the polymeric membrane liners currently manufactured are based on unvulcanized or uncrosslinked compounds and thus are thermoplastic. Even if the polymer in the vulcanized form is more chemically resistant (such as CPE and CSPE), it is generally supplied unvulcanized because it is easier to obtain reliable seams and to make repairs in the field. Thermoplastic polymers can be heat-sealed or seamed with a solvent or bodied solvent (a solvent containing dissolved polymer to increase the viscosity and reduce the rate of evaporation). Crystalline sheetings, which are also thermoplastic, are seamed by thermal welding or fusion methods. Information on individual polymers and liners is presented in the EPA Technical Resource Document on liners (Matrecon, 1982).

TABLE 2.BASIC COMPOSITIONS OF POLYMERIC MEMBRANE LINER COMPOUNDS

Component	Type of polymeric compound		
	Crosslinked	Thermoplastic	Crystalline
Polymer or blends (alloys)	100	100	100
Oil or plasticizer	5-40	5-40	0-10
Fillers:			
Carbon black	5-40	5-40	2-5
Inorganics	5-40	5-40	---
Antidegradants	1-2	1-2	1
Crosslinking system:			
Inorganic system	5-9	(*)	---
Sulfur system	5-9	---	---

*An inorganic curing system that crosslinks over time is incorporated in CSPE liner compounds.

ANALYSIS AND FINGERPRINTING OF UNEXPOSED POLYMERIC LINING MATERIALS

Analyses of liners run before and after exposure to different environments include:

- Volatiles
- Ash
- Extractables
- Gas chromatography
- Thermogravimetric analysis
- Differential scanning calorimetry if liner material is crystalline
- Specific gravity

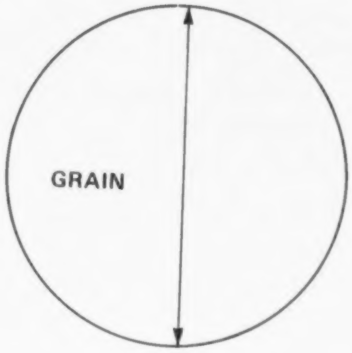
The following subsections describe the tests performed on unexposed polymeric linings.

Volatiles

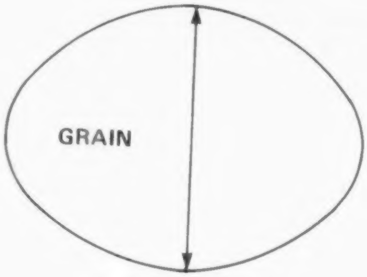
The volatile fraction is represented by the weight lost by an unexposed specimen of the liner on heating in a circulating air oven at 105°C for 2 hr. Polymeric compositions generally contain a small amount of volatiles (<1.0%), usually moisture. The recommended specimen is a disk cut from the membrane.

The volatiles test can also be used to determine the direction of the grain that has been introduced in the membrane during manufacture. By identifying the orientation of the 2-in. disk specimen with respect to the sheeting at the time the specimen was died out, the grain direction can be identified. The grain direction must be known so that tensile and tear properties can be determined in machine (grain) and transverse directions. Upon heating in the oven at 105°C, sheeting with a grain will shrink more in the grain direction than in the transverse direction (Figure 1).

Volatiles need to be removed before determining ash, extractables, and specific gravity. Ash and extractables are reported on a dry basis (db). Volatiles contents of representative membrane liners are presented in Table 3. Monomeric plasticizers that are generally used in PVC compositions have a limited volatility and can slowly volatilize at 105°C. Thus the air oven test must be limited to 2 hr.



As received



After air oven heating
2 hr. at 105°C

Figure 1. Machine direction determinations.

A standard test for the volatility of plasticizers in PVC compounds is performed in accordance with ASTM D1203. In this test, activated charcoal is used to absorb volatilized plasticizer.

Ash

The ash content of a liner material is the inorganic fraction that remains after a devolatilized sample is thoroughly burned at 550°±25°C. The ash consists of (1) the inorganic materials that have been used as fillers and curatives in the polymeric coating compound, and (2) ash residues in the polymer. Different liner manufacturers formulate their compounds differently, and determining the ash content can be a way to "fingerprint" a polymeric liner compound. The residue obtained by ashing can be retained for other analyses (such as metals content) needed for further identification and for providing a reference point to determine trace metals that may have been absorbed by the liner. The test method described in ASTM D297, Section 34, is generally followed in performing this analysis. Ash contents of representative membrane liners are presented in Table 3.

Extractables

The extractable content of a polymeric sheeting is the fraction of the compound that can be extracted from a devolatilized sample of the liner with a solvent that neither decomposes nor dissolves the polymer. Extractables consist of plasticizers, oils, or other solvent-soluble constituents that impart or help maintain specific properties such as flexibility and processability. A measurement of extractable content and an analytical study of the extract can be used as part of the fingerprinting of a sheeting.

During exposure to a waste, the extractable constituents in a liner may be removed and result in property changes. At the same time during exposure, the liner might absorb nonvolatilizable constituents from a waste. Measuring the extractable content of unexposed lining materials is therefore useful for monitoring the effects of exposure. The extract and the extracted liner obtained by this procedure can be used for further analytical testing (e.g., gas chromatography, infrared spectroscopy, ash, thermogravimetry, etc.) and fingerprinting of the liner.

The procedure for extraction generally follows ASTM D3421, "Extraction and Analysis of Plasticizer Mixtures from Vinyl Chloride Plastics". Also see ASTM D297, "Rubber Products-Chemical Analysis", paragraphs 16-18.

Because of the wide differences among the polymers used in liner manufacture, a variety of extracting media must be used.

TABLE 3. ANALYSIS OF UNEXPOSED POLYMERIC MEMBRANE LINERS*,†

Polymer	Base polymer, specific gravity	Compound			
		Specific gravity	Volatiles, %	Extractables, %	Ash, %
Butyl rubber	0.92	1.206	0.45	10.96	5.25
		1.176	0.46	11.79	4.28
Chlorinated polyethylene	1.16-1.26	1.360	0.10	7.47	14.40
		1.362	0.00	9.13	12.56
		1.377	0.05	...	17.37
Chlorosulfonated polyethylene	1.11	1.433	0.84	1.49	33.95
		1.343	0.51	3.77	3.28
Elasticized polyolefin	0.92	0.938	0.15	5.50	0.90
Epichlorohydrin rubber	1.27-1.36	1.490	0.63	7.27	4.49
Ethylene propylene rubber	0.86	1.173	0.38	23.41	6.78
		1.122	0.50	31.77	5.42
		1.199	0.31	18.16	0.32
Neoprene	1.25	1.503	0.76	10.15	12.98
		1.480	0.19	13.43	13.43
		1.390	0.37	21.46	4.67
Polybutylene	0.91	0.915	0.12	...	0.08
Polyester elastomer	1.17-1.25	1.236	0.26	2.74	0.38
Polyethylene (low density)	0.92	0.921	0.18	2.07	0.13
Polyethylene (high density)	0.96	0.961	0.12	0.49	0.46
Polyethylene (high density) alloy	0.95	0.949	0.11	2.09	0.32
Polyvinyl chloride	1.40	1.275	0.11	33.90	6.20
		1.264	0.09	37.25	5.81
		1.231	0.05	38.91	3.65
		1.280	0.31	35.86	6.94
		1.308	0.03	25.17	5.67

*Source of some of the data: Haxo et al. (1982).

†Multiple figures represent materials from different manufacturers.

Table 4 lists the recommended solvents for extraction of membrane liners of each polymer type.

Typical values for the extractables in polymeric membranes are given in Table 3.

Gas Chromatography

Gas chromatography can be used to find the level of the plasticizer (e.g., diethylhexyl phthalate (DEHP), a dioctyl phthalate) compounded into a PVC liner material. Figure 2 shows the quantification of DEHP in the solvent extract of a PVC liner material. The weight percent of the DEHP in the liner can then be calculated, assuming the extraction to be 100% efficient. A typical procedure is summarized below.

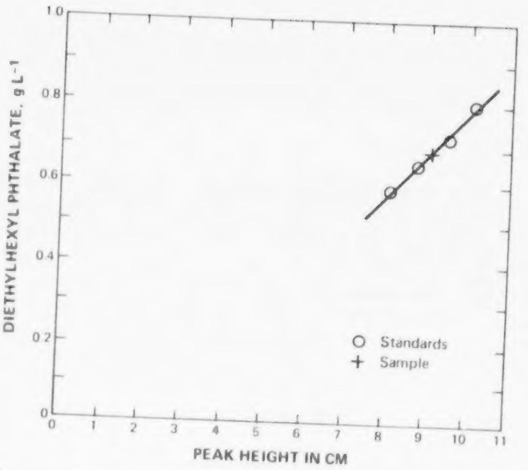


Figure 2.Gas chromatograph determination of the diethylhexyl phthalate content in an extract of a PVC membrane. Column: 6'x1/8" 3% OV 101 on Chromosorb WHP. Temperature: 200°-300°C at 8°C/min. He carrier gas: at 30cc/min.

A weighed sample of liner is extracted with an appropriate solvent. The extract is evaporated to dryness over a steam bath. The dry residue is redissolved in solvent and brought to an accurately known volume. Following the development of appropriate chromatographic conditions, injection of this solution into the instrument will separate it into chemically pure components characterized by different retention times. An injection of a DEHP standard solution will identify the retention time of the DEHP component. Comparison of the peak height (area) data obtained from the injection of equal volumes of the extract solution and from quantitatively prepared standard solutions allows the interpolation of the DEHP concentration in the extract solution (Figure 2).

TABLE 4. SOLVENTS FOR EXTRACTION OF POLYMERIC MEMBRANES*

Polymer type	Extraction solvent
Butyl rubber (IIR)	Methyl ethyl ketone
Chlorinated polyethylene (CPE)	n-Heptane
Chlorosulfonated polyethylene (CSPE)	Acetone
Elasticized polyolefin	Methyl ethyl ketone
Epichlorhydrin rubber (CO and ECO)	Methyl ethyl ketone or acetone
Ethylene propylene rubber (EPDM)	Methyl ethyl ketone
Neoprene	Acetone
Nitrile rubber (vulcanized)	Acetone
Nitrile-modified polyvinyl chloride	2:1 blend of carbon tetrachloride and methyl alcohol
Polyester elastomer	Methyl ethyl ketone
High-density polyethylene (HDPE)	Methyl ethyl ketone
Polyvinyl chloride (PVC)	2:1 blend of carbon tetrachloride and methyl alcohol
Thermoplastic olefinic elastomer	Methyl ethyl ketone

*Because lining materials can be sheetings based on polymeric aloys marketed under a trade name or under the name of only one of polymers, this list can only be taken as a guideline for choosing a suitable solvent for determining the extractables. Once a suitable solvent has been found, it is important that the same solvent be used for determining the extractables across the range of exposure periods.

Pyrolysis gas chromatography

Pyrolysis gas chromatography is an alternative method for measuring a plasticizer in liner materials. In this technique, a small, weighed sample of liner is heated very rapidly to a temperature sufficient to volatilize all of its organic components. The plasticizer and other lower-molecular weight organics will be driven off as chemically unchanged vapors. The polymer will undergo pyrolysis, or high temperature decomposition, and will volatilize as lower-molecular-weight organic compounds. The resulting volatiles may be separated and quantified by gas chromatography as previously described, and the plasticizer content of the liner may be calculated.

This method has the strong advantage of not requiring extraction of the liner sample, but it may not be as reliable a means of quantification because of the very small sample size and the large number of components that must be separated by the gas chromatograph.

Thermogravimetric analysis (TGA)

TGA is a thermal technique for assessing the composition of a material by its loss in weight on heating at a controlled rate in an inert or oxidizing atmosphere. For example, when a material is heated in an inert atmosphere from room temperature to 600°C at a controlled rate, it will volatilize at different temperatures until only carbon, char and ash remain. The introduction of oxygen into the system will burn off the char and carbon black. Thus from the weight-time curve which can be related to weight and temperature, the amounts of volatiles, plasticizer, polymer, carbon black, and ash can be calculated. In some cases, thermogravimetric analysis can replace measurements of the volatiles, ash, and extractables contents discussed above. The TGA curve and the derivative of the TGA curve can thus be used as part of a fingerprint of a polymeric composition. This technique is described by Reich and Levi (1971).

A Perkin-Elmer TGS-2 thermogravimetric system, consisting of an analyzer unit, balance control unit, heater control unit, and first derivative computer, is used in our laboratory. Temperature control is supplied by the temperature controller on the Perkin-Elmer DSC-2 (Differential Scanning Calorimeter). A double side-arm furnace tube was used to allow rapid changing of the atmosphere from inert (N_2) to oxidative (N_2/O_2 mixture). For the oxidative atmosphere, N_2 purge is maintained through the analyzer unit head, and O_2 is introduced at the upper side arm where it mixes with the N_2 to burn the carbon black and any carbonaceous residue that forms during the pyrolysis of the polymer. Use of the double side-arm furnace tube shortens the turnaround time because it eliminates the need to flush the analyzer head completely to remove O_2 between runs, as would be necessary if O_2 were introduced through the head. A dual pen recorder Perkin-Elmer Model 56 allows a simultaneous display of thermocouple temperature in the furnace and the change in weight of the specimen or the first derivative of the change in weight.

An example of the TGA procedure for the analysis of a polymeric liner is described below.

A 5-mg specimen of the liner was placed in the balance pan and weighed in a nitrogen flow of 40 cc/min. The instrument was adjusted to give a 100% full-scale deflection for the weight of the sample, so the percent of weight change can be read directly from the chart.

The specimen was heated to 110°C and held there for 5 min to determine whether measurable volatiles were present; it was then heated from 110° to 650°C at a rate of 20°C/min in a nitrogen atmosphere. The specimen was held at 650°C until no more weight loss occurred, usually 2 to 3 min, after which it was cooled to 500°C and O_2 was introduced at a rate of 10 cc/min with an N_2 flow rate of 30 cc/min.

Typical thermograms for HDPE and EPDM appear in Figures 3 and 4, respectively. Analyses of a variety of polymeric membrane liners are presented in Table 5.

Differential Scanning Calorimetry (DSC)

DSC is a thermal technique for measuring the melting point and the amount of crystallinity in partially crystalline polymers such as the polyolefins polyethylene, polypropylene, and polybutylene. This technique measures the heat of fusion of a crystalline structure; it can also give an indication of the modification of crystalline sheeting with other polymers

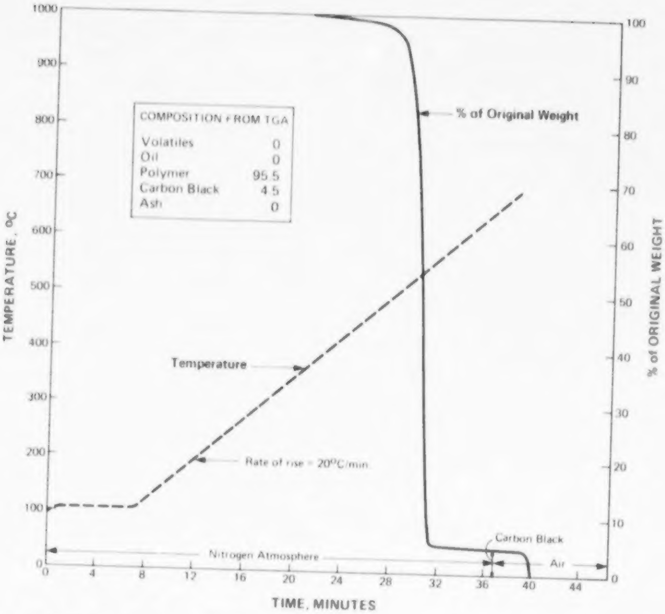


Figure 3.TGA of an unexposed black HDPE liner. The plots of sample weight and temperature as a function of time are shown. Under an N_2 atmosphere, the black HDPE sample lost approximately 95.5% of its mass as hydrocarbons were evolved. The carbon black added as an ultraviolet light absorber remained as a carbonaceous residue and was not volatilized until it was oxidized when oxygen was allowed into the system.

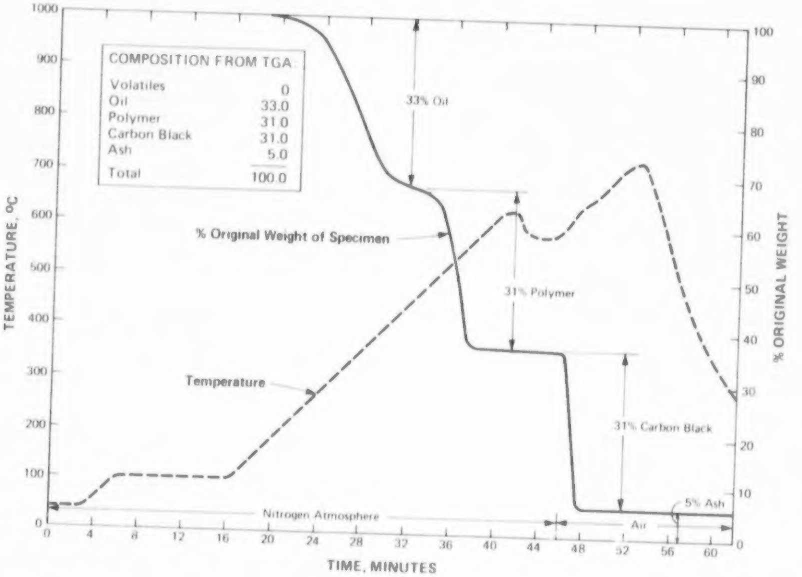


Figure 4.Thermogravimetric analysis of an unexposed EPDM liner membrane. The dotted line shows the temperature program and the solid line shows the percent of the original specimen weight. At 46 minutes the atmosphere was changed from nitrogen to air to burn the carbon black.

TABLE 5.THERMOGRAVIMETRIC ANALYSIS OF POLYMERIC MEMBRANE LINERS

Polymer type	Volatiles, %	Polymer, %	Oil or plasticizer, %	Carbon black, %	Ash, %
Butyl rubber	0	45.0	12.2	37.1	5.7
Chlorinated polyethylene	0	72.2	7.6	5.3	14.9
	0	71.3	9.1	6.5	13.1
	0.4	53.9	13.9	21.0	10.8
Chlorosulfonated polyethylene	1.0	49.3	1.5	45.6	2.6
	0.9	47.7	3.2	45.2	3.0
	0.1	58.1	5.5	9.8	26.5
Elasticized polyolefin	0	93.1	1.7	4.0	1.2
Epichlorhydrin rubber	0	49.3	8.2	37.7	4.8
Ethylene propylene rubber	0.1	30.8	32.9	30.9	5.3
	0.2	33.5	23.2	35.5	7.6
Neoprene	1.0	42.3	10.7	34.9	11.1
	0	44.0	10.7	33.8	11.5
Polyethylene (high density)	0	97.9	0	2.1	...
	0	95.6	0	4.2	0.2
	0	97.0	0	1.8	1.2
Polyvinyl chloride	0	48.7	38.2	6.2	6.9
	0	46.0	42.1	7.8	4.1
	0	51.0	35.0	7.0	7.0

by alloying. Thus this type of analysis can be used as a means of fingerprinting crystalline polymeric liner materials (particularly high-density polyethylene) and assessing the effects of aging and exposure to wastes. This technique is described by Boyer (1977) and Ke (1966).

The differential scanning calorimeter used in this work was the Perkin-Elmer Model DSC-2C, equipped with an Intracooler I subambient temperature accessory to provide an operating temperature range of -40 to 725°C.

The equipment is used to characterize the thermal transitions of materials such as melting, boiling, and changes in crystal structure. A sample and reference cell are provided. A weighed sample is placed in the sample holder; the reference cell is generally run empty to provide an absence of thermal transitions. The two cells are simultaneously heated or cooled so that the average cell temperature follows a preset program. When the sample undergoes a thermal transition, an endothermic or exothermic reaction will occur. The change in power required to maintain the sample cell at the same temperature as the reference cell is recorded as a deflection of the recorder pen. The recorder plots the temperature (°C) versus the differential energy flow (mcal/sec) required to maintain the sample cell temperature. An endothermic transition such as melting is shown as a positive peak; an exothermic reaction such as crystallization is shown as a negative peak. The magnitudes of these peaks and the temperatures at which they occur are characteristic of the material analyzed.

An example of the use of the DSC to determine the polyethylene crystallinity in an HDPE liner is shown in Figure 5.

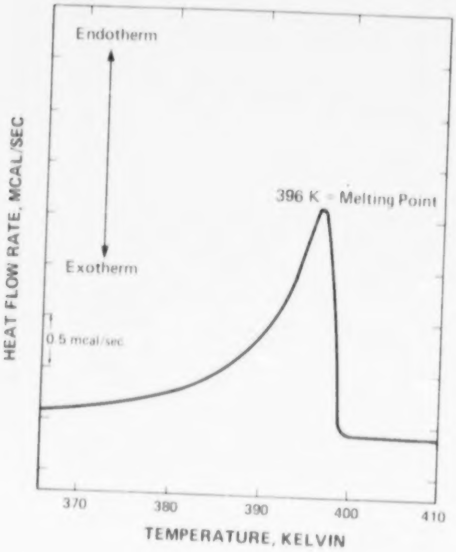


Figure 5. DSC determination of the polyethylene crystallinity in an HDPE liner. The x-axis is the temperature which was raised at 5°C/min. The y-axis is calibrated in mcal/sec, or rate of energy flow. A positive deflection of the plot indicates that the sample is absorbing energy (e.g., during melting). The amount of energy absorbed during the melting process may be determined by calculating the peak area and relating it to the peak area resulting from the melting of an Indium standard of known weight. The energy absorbed is termed the "heat of fusion" (H_f). Assuming that H_f for the fully crystalline polymer is known, the degree of crystallinity of the sample can be determined as a simple ratio.

Specific gravity

Specific gravity is an important characteristic of a material and is generally easy to determine. Because of differences in the specific gravities of the base polymers, specific gravity of the liner compound can give an indication of the composition and identification of the polymer. Specific gravities of base polymers and of different liner compounds based on them are presented in Table 3. They show the differences among polymers and the variations in compounds from one manufacturer to another.

ASTM Method D792, Method A-1, and D297, Section 15.1.2, Hydrostatic Method, are generally used in performing this test.

ANALYSIS AND FINGERPRINTING OF EXPOSED POLYMERIC MEMBRANE LINERS

During service, several processes can take place to change the composition of a liner and thus affect physical properties and possibly performance. First, the liner can absorb waste liquids including water, various organics, and possibly some inorganic substances. The composition of the absorbed chemicals will probably reflect that of the waste liquid, but it will vary depending on the relative solution characteristics and the waste liquid constituents. The absorbed organics can be both volatile and nonvolatile. The total amount generally softens the liner, resulting in possible loss of tensile strength and other mechanical properties, loss of elongation, and increased permeability. While the organic constituents are being absorbed, some of the extractables such as plasticizer and oils may migrate out of the compound, either by evaporation, dissolution in waste liquid, or biodegradation. Severe loss of plasticizer could result in stiffening and loss in mechanical properties. Losses in properties can occur also through UV degradation and oxidation of the polymer if the liner is exposed to the weather. Figure 6 schematically represents the compositions of a polymeric liner before and after exposure and after extractions.

In assessing the long-term effects of exposure to wastes and the other conditions in a disposal facility, it is necessary to know which waste constituents have affected the lining material and what degradation may have taken place. An analysis of exposed liners is most useful to determine these factors. Figure 7 illustrates a proposed plan of analysis that we have used in our analyses of exposed materials, recovered from the laboratory or the field.

The various tests that are performed on exposed membranes are the same as those discussed in the previous section for unexposed lining materials, with modifications and special precautions required in each test for the exposed materials. These individual tests are described in the following subsections.

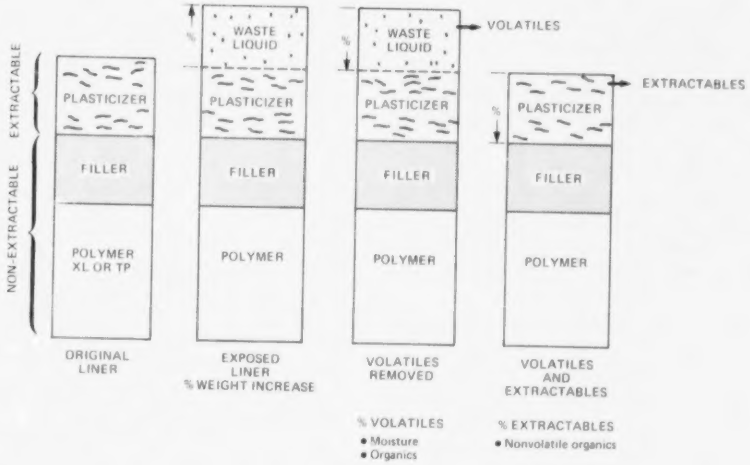
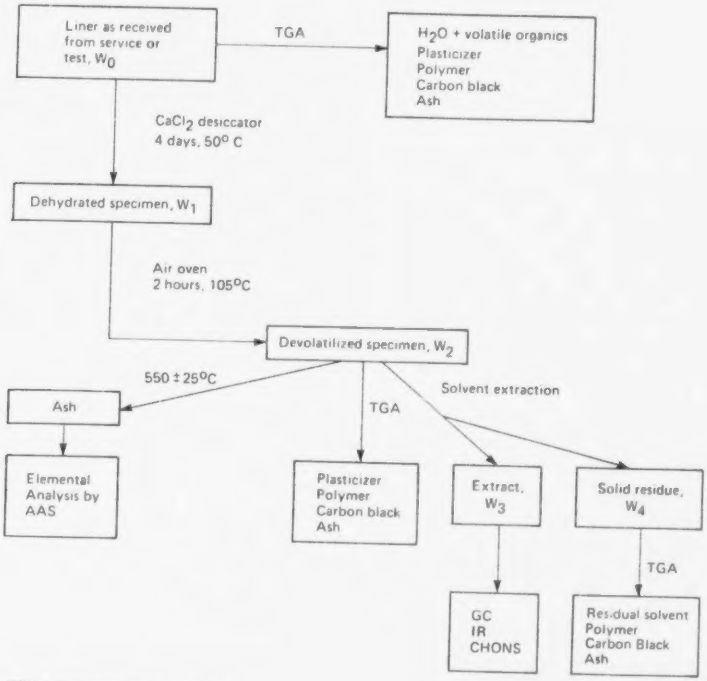

EXTRACTABLE
NON-EXTRACTABLE
PLASTICIZER
FILLER
POLYMER XL OR TP
ORIGINAL LINER
WASTE LIQUID
%
PLASTICIZER
FILLER
POLYMER
EXPOSED LINER % WEIGHT INCREASE
WASTE LIQUID
VOLATILES
%
PLASTICIZER
FILLER
POLYMER
VOLATILES REMOVED
% VOLATILES
• Moisture
• Organics
EXTRACTABLES
%
PLASTICIZER
FILLER
POLYMER
VOLATILES AND EXTRACTABLES
% EXTRACTABLES
• Nonvolatile organics

Figure 6. Schematic presentation of changes in composition of a polymeric liner compound on exposure to a waste liquid, on removal of volatiles, and on extraction with an appropriate solvent.


Liner as received from service or test, W_0
TGA
H_2O + volatile organics
Plasticizer
Polymer
Carbon black
Ash
$CaCl_2$ desiccator
4 days, 50° C
Dehydrated specimen, W_1
Air oven
2 hours, 105°C
Devolatilized specimen, W_2
550 ± 25°C
Ash
TGA
Solvent extraction
Elemental Analysis by AAS
Plasticizer
Polymer
Carbon black
Ash
Extract, W_3
Solid residue, W_4
TGA
GC
IR
CHONS
Residual solvent
Polymer
Carbon Black
Ash

TGA = thermogravimetric analysis
GC = gas chromatography
IR = infrared spectroscopy
AAS = atomic absorption spectroscopy
CHONS = carbon, hydrogen, nitrogen, oxygen, and sulfur determination

Figure 7. Plan for the analysis of exposed polymeric lining materials.

Volatiles

The initial analytical test generally performed is a determination of the volatiles content, which gives an indication of the amount of waste liquid that has been absorbed by the liner. As an approximation, the weight increase can be calculated by dividing the percent of volatiles by the percent of nonvolatiles. For example, if the volatiles are 15%, and the nonvolatiles are 85%, the percent increase in weight based on the original liner would be 17.6%.

Inasmuch as the volatiles contain both water and organic components, it is desirable to separate these two. A study was made to dehydrate the specimens of the exposed liner to remove the water. A series of desiccants was studied at room temperature and 50°C. Four days of exposure of the exposed liner at 50°C in a small individual desiccator containing calcium chloride removed the moisture from the 2-in. disk specimen without removing organic constituents. After removal of the water, a 2-hr heating of the specimen in a circulat-ing air oven removed the remaining organic volatiles. Collection of the organic volatiles and determination of composition by gas chromatography would be desirable but has not been attempted to date. The water and the organic volatiles equal the volatiles obtained in bypassing the desiccator exposure. Such a bypass removes the moisture by exposure at room temperature for 1 week in moving air followed by heating in a circulating air oven for 20 hr at 50°C and 2 hr at 105°C. We have found, however, that the highly swollen CPE liner may take up to 6 days at 50°C to come to constant weight. The time required to remove volatiles depends on the thickness and permeability of the liner and the care taken to avoid the "skin" that forms on the surface of the specimen when using too high an initial temperature to devolatilize. After the volatiles are removed, the exposed materials can be subjected to the other tests, including specific gravity, extractables, ashing, etc.

Total volatiles can also be determined through the use of TGA which is discussed below.

Extractables

Extractables of exposed materials will probably differ from the original values because of the loss to the waste liquid and absorption of nonvolatile organics (e.g., oils). After the volatiles have been removed from the liner, the extractables are determined by the same method used on the unexposed liner materials. Examples of extractable contents after exposure are given in Table 6. If the liner has been in contact with wastes containing nonvolatile constituents, the extractables recovered may be greater than the original values. Analysis of the extractables by gas chromatography and infrared analysis may give an indication of the nonvolatile organics that were absorbed. The analysis of the extractables will give an indication of the constituents of the waste that are aggressive to the liner, as they are the constituents that have been absorbed. They may show up in minor amounts in a waste analysis, but because of their chemical characteristics such as solubility parameters and hydrogen bonding, they may be scavenged by the polymeric liner.

Ash

The ash content of an exposed membrane liner is determined after the volatiles have been removed from the specimen. As in the case of the unexposed membrane, the exposed liner is ashed in a muffle furnace at 550°C. The ash value usually differs from that of the unexposed material, depending on how many nonvolatile organics were lost or gained during the exposure period. If plasticizer is lost, the value will increase because of the nonash content of the plasticizer. Also, if any organic metal compounds are absorbed by the liner, they will show as an increased ash content. A comparison of the elemental analysis of the ash with that of the original liner will determine whether any absorption of metal species occurred during the exposure. No such absorption has been observed, but metal organics might be absorbed by a liner. In general, the inorganics that make up the ash are retained in the liner and maintain a constant ratio with respect to the polymer content, as polymer is generally not dissolved by the waste liquid.

Thermogravimetric analysis

The TGA analysis can be used to give a quick analysis of the composition of an exposed polymeric membrane liner. The test is run similarly to that of the unexposed material, except that care must be taken in handling the small specimens of exposed

TABLE 6.EXTRACTABLES OF DIFFERENT POLYMERIC MEMBRANE LINERS BEFORE AND AFTER VARIOUS EXPOSURES

Polymer	Unexposed	Type of exposure by waste	Extractables after exposure
Butyl rubber	11.79	Aromatic oil	27.23
		Spent caustic	10.87
		Oil 104	40.34
Chlorinated polyethylene	9.13	Oil 104	17.00
		Roof exposure	5.99
Chlorosulfonated polyethylene	4.08	Aromatic oil	59.81
		Oil 104	15.92
		Slop water	3.70
Elasticized polyolefin	5.50	Oil 104	20.74
		Aromatic oil	23.37
		Slop water	2.96
Ethylene propylene rubber	23.64	Aromatic oil	38.35
		Oil 104	43.45
		Spent caustic	22.89
Neoprene	21.46	Aromatic oil	58.47
		Oil 104	23.85
		Slop water	17.63
Polyvinyl chloride	33.90	Aromatic oil	40.55
		Roof exposure	26.27
		Pesticide	35.38
		Oil 104	17.95

liners that contain the volatiles. These volatiles can be easily lost. Figure 8 is a thermogram of an exposed PVC membrane liner that had absorbed more than 7% of the waste liquid, which was predominantly water. The results are shown on the figure, but the losses show the effect of the char formation of the PVC when it is heated in a nitrogen atmosphere. Chlorinated polymers lose HCl and leave a char for which correction must be made in the calculations of the polymer content. These calculations have been made on the figure, and the results compare favorably with those obtained by direct analysis of the volatiles, extractables, and ash.

Specific gravity

The specific gravity of exposed membrane liners is also determined after the membrane specimen has been thoroughly devolatilized. Three steps must be taken to avoid the formation of bubbles in the liner mass during a direct devolatilizing process (which would affect the specific gravity results). First, the specimens must be allowed to "dry" at room temperature in an air stream in a hood until constant weight is achieved, which could take several days. Second, they must be placed in an oven at 70°C for 16 hr; and third, they must be heated at 105°C for 2 hr.

The specific gravity of an exposed membrane can differ from that before exposure, depending on how much of the original extractable material was lost and how much material from the waste was absorbed during exposure. The procedure followed was ASTM D297 using the hydrostatic method.

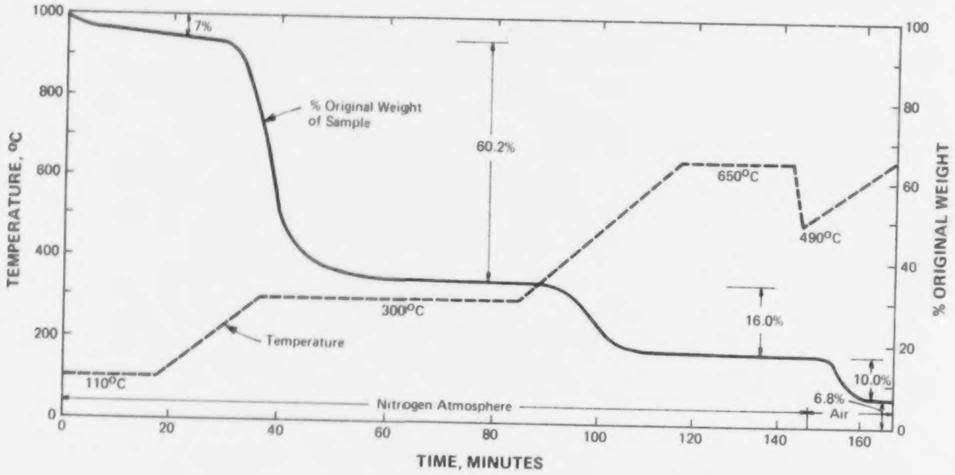


Figure 8. TGA of an exposed polymeric PVC liner.

Weight loss A = 7.0% volatiles = moisture + possible organics.
Weight loss B = 60.2% = plasticizer + HCl from the polymer (PVC).
Weight loss C = 16.0% = residual polymer.
Weight loss D = 10.0% = carbonaceous polymer residue + carbon black.
Residue weight E = 6.8% = ash.

Composition of the exposed liner as received calculated from above data. Values by direct analysis are shown in parentheses.

Volatiles	7.0% (7.9)[a]
Polymer (PVC)	44.7%
Plasticizer	34.1% (32.2% as extractables)[a]
Carbon black	7.4%
Ash	6.8% (6.4)[a]

[a] By direct analysis.

SUMMARY AND CONCLUSIONS

A protocol is presented for the analysis of polymeric membrane lining materials before and after exposure to waste liquid.

The results of the analysis can be used as a fingerprint of the unexposed liner and as a baseline for assessing the changes that occurred during exposure to a waste liquid.

The analysis of an exposed liner furnishes information regarding the change in the composition of the membrane and the chemical materials that are actually absorbed during exposure. This latter information indicates the constituents of the waste that are aggressive to the lining material.

Thermal analysis and gas chromatography are particularly useful in the analysis and fingerprinting of polymeric membranes.

The use of gas chromatography coupled with mass spectroscopy needs to be investigated to determine the specific chemicals that are absorbed by a polymeric liner.

The use of this analysis may lead to techniques which will better predict the service life of a flexible membrane liner.

ACKNOWLEDGEMENTS

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The author wishes to thank Robert E. Landreth, Project Officer, for his support and guidance in these projects.

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EVALUATION OF A WASTE IMPOUNDMENT LINER SYSTEM AFTER LONG-TERM EXPOSURE

by

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ABSTRACT

Samples of a 20-mil polyvinyl chloride (PVC) liner in use for 9 years in an industrial sludge lagoon that contained a calcium sulfate slurry were collected and tested. The lagoon was scheduled to be excavated and relined because of mechanical damage to the liner; therefore, samples were available for studying the effects of long-term exposure of lining materials to wastes.

Eighteen samples of the liner were collected from the berm, side slopes, and bottom of the lagoon. Nine samples were selected for analysis and physical testing to assess the effects of directional orientation of weather exposure and the effects of sludge exposure. They included samples from the north, south, east, and west sides, from under sludge at different depths, samples of factory and field seams, and any anomalous samples. Measurements were made of tensile strength, tear strength, puncture resistance, hardness, seam strength, volatiles content, and extractables content.

Results of the testing show that exposure of the liner to the weather had the greatest effect on the PVC liner, with the samples facing south being most severely affected. Judging by their low extractables, the weather-exposed samples lost plasticizer; they had low elongation at break values, high hardness values, and some were brittle. The samples exposed to the sludge or soil had higher extractables and elongation at break values and lower hardness values than weather-exposed specimens. Two samples taken from the lagoon bottom had comparable properties to those of unexposed 20-mil PVC liners. The factory seams were in good condition. A sample of the field seam, however, contained an unbonded section and failed in the glue line in shear testing, indicating an inadequate seam.

INTRODUCTION

A considerable number of laboratory tests and pilot-scale studies are currently being conducted to assess the effects on polymeric membrane liners from exposure to industrial wastes. However, limited information is being collected to assess the performance of liners at industrial sites and lagoons (1,2). The scarcity of information is partly due to the short time period during which liners have been in use in waste impoundments and the problems associated with obtaining liner samples from impoundments.

The purpose of this study, conducted by Malcolm Pirnie, Inc. and Matrecon, Inc. was to provide field verification of laboratory testing methods of polymeric liners and to evaluate site-specific effects of hazardous waste disposal on the performance of a polymeric liner.

In August and September 1982, Malcolm Pirnie, Inc., collected samples of a 20-mil polyvinyl chloride (PVC) liner from an industrial sludge lagoon. The lagoon was scheduled to be excavated and relined; thus it was possible to obtain samples of the exposed PVC liner. The liner samples were tested to determine properties of the liner after a service period of 9 years.

BACKGROUND

The site is located in the northeast United States. The lagoon was constructed in 1973, and a PVC liner was installed.

The lagoon, which is approximately 85 ft wide, 240 ft long, and 9 ft deep, has a generally north-south orientation and a side slope of approximately 2:1. The PVC liner was fabricated by the supplier in two pieces, which were seamed in the field by the installer. This field seam runs the length of the lagoon and bisects the 85-ft side as shown in Figure 1. The factory seams run parallel to the field seam. All seams appear to have been made using a bodied solvent. In the corners of the lagoon, the liner was folded into place. An anchor trench was not used to secure the liner over the berm; instead, the upper edge of the liner was folded and soil was placed on it. The PVC liner was designed to be covered during the lagoon operation; although a sand layer covered it initially, it sloughed off the top of the berm.

The lagoon was used as a settling basin where a slurry waste was pumped in, the solids were allowed to settle, and the liquid was pumped back into the plant. When the lagoon was filled, at approximately 1- to 2-year intervals, the contents were removed and landfilled onsite. A clamshell was used to scoop out the contents, except for a thin layer of sludge that was left on the liner to avoid damaging it. The liner was reported to have been snagged on occasion and punctured by the clamshell.

The waste disposed of in the lagoon is a calcium sulfate sludge, the result of the neutralization of sulfuric acid with lime. The sludge also contains ammonia and chlorides. The sludge is a fine-grained, generally greyish-white moist solid. In the lower portion of the lagoon, the pore spaces in the sludge are completely filled with a precipitation/ground-water/waste liquid. This is termed the saturated portion of the sludge. In the upper portion of the lagoon, the pore spaces in the sludge are not always completely filled with the liquid. This is termed the unsaturated portion of the sludge. The location of the unsaturated/saturated zone interface has moved up and down during the operation of the lagoon. However, the sludge at the bottom of the lagoon probably remained saturated throughout the life of the lagoon. The pH of the lagoon liquid varied from 8 to 9 at the times the liner samples were collected. A general analysis of the waste liquid in the lagoon is presented in Table 1; this is probably the best representation available of the liquid in contact with the inside of the PVC liner in the saturated sludge portion of the lagoon slope.

TABLE 1.

GENERAL ANALYSIS OF SLUDGE LIQUID

Item	Amount
pH	8.0 - 9.0
Specific conductance, µmhos	15,000 - 60,000
Chlorides, mg/L	4,500 - 5,000
Sulfates, mg/L	15,000 - 20,000
Ammonia, mg/L	1,000 - 7,000

The lagoon is underlain by glacial deposits that overlie fractured crystalline bedrock. The glacial deposits consist of outwash material made up of well-graded to poorly graded sands and silts, underlain by till made up of unstratified, poorly sorted sands, silts, and gravel with some cobbles and boulders. A natural organic/peat layer overlies part of the glacial material, and fill is present in some areas around the lagoon. The water table, or the top of the ground-water surface, was approximately 6 to 8 ft below the ground surface in the area of the lagoon; thus the bottom of the lagoon would have been in the ground water. Leakage from the lagoons appears to have contributed to a ground-water mound in the vicinity of the lagoon. In addition, seasonal ground-water level fluctuations resulted in alternate wetting/drying cycles of the soil on the outside of the liner.

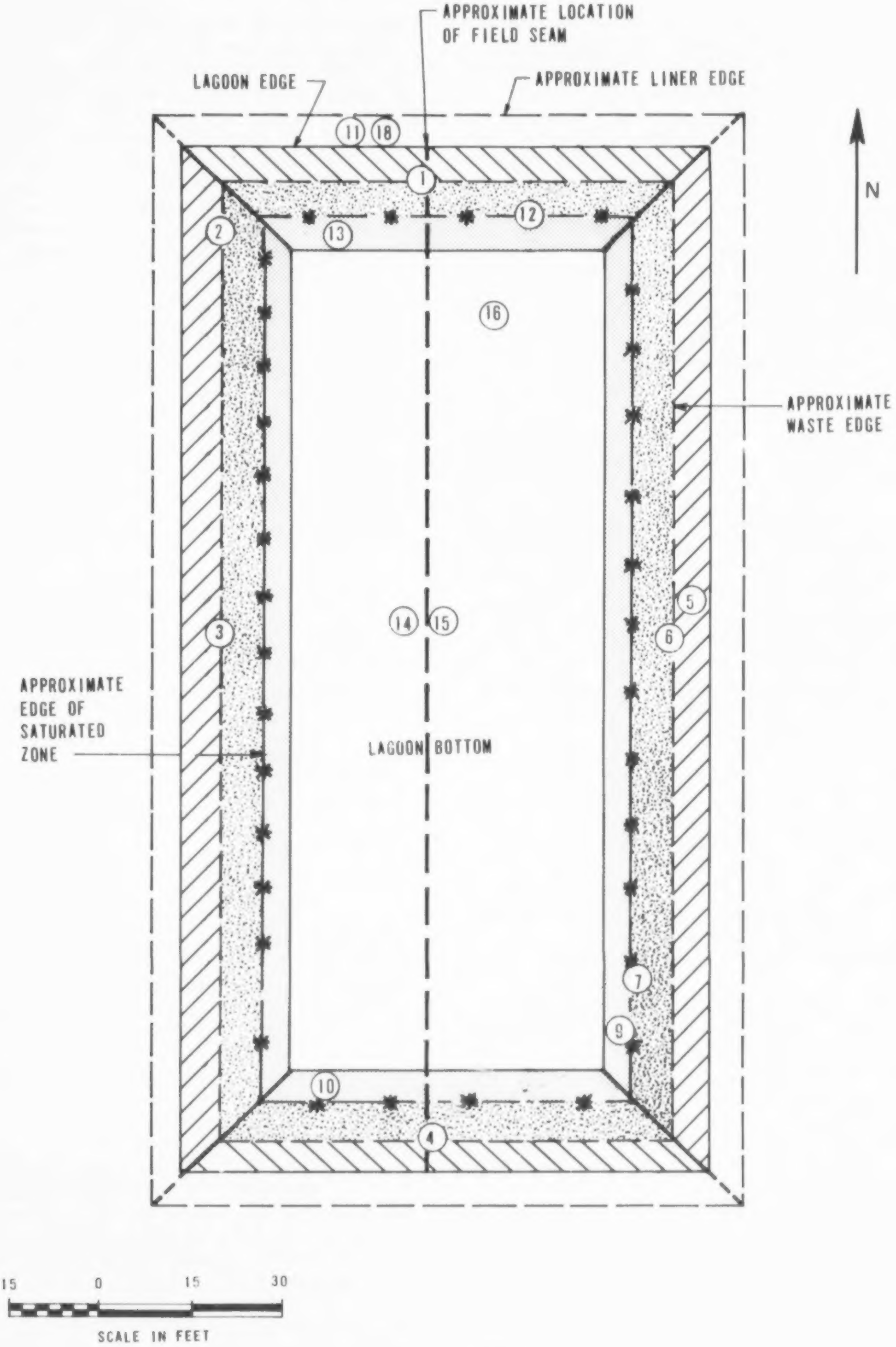
APPROXIMATE LOCATION OF FIELD SEAM
LAGOON EDGE
APPROXIMATE LINER EDGE
N
11
18
1
12
13
2
16
APPROXIMATE WASTE EDGE
5
3
14
15
6
APPROXIMATE EDGE OF SATURATED ZONE
LAGOON BOTTOM
7
9
10
4
15
0
15
30
SCALE IN FEET

Figure 1 (See figure legends list)

PROCEDURES

SAMPLING

Samples of the PVC lagoon liner were obtained according to the procedure developed by Matrecon, Inc. The samples were rolled up and wrapped with aluminum foil, then placed in a polyethylene bag and boxed for shipment. Six liner samples were taken from the upper edge of the lagoon in August 1982. Subsequently, 12 additional liner samples were taken from the lagoon sides and bottom in September 1982, when the lagoon was being excavated. Matrecon diagrammed and photographed the liner samples upon receipt; they were then resealed to minimize loss of any volatiles before analysis and testing. In addition, samples of the sludge above the PVC liner and of the soil below it on the lagoon bottom were collected in September 1982.

The lagoon liner sampling locations are shown in Figure 1. Two techniques were used to obtain the samples. The samples located in the upper portion of the lagoon, i.e., the weather-exposed samples and the unsaturated zone samples, were cut out directly from the side of the lagoon. The samples located in the lower portion of the lagoon were taken out by the clamshell, then cut to size.Use of the clamshell was necessary since the lower portion of the lagoon was filled with a mixture of saturated sludge and ground water, and direct access was impossible.

Field observations of the liner samples are in Table 2.

Ten of the 18 liner samples were selected for testing based on the following criteria:

- A sample with minimal or no exposure to sun or sludge to use as a possible control, since no retained sample was available. This sample was taken from the upper edge where the liner had been covered with soil. It is possible that this sample was exposed to sludge.
- Samples exposed to the weather from north, south, east, and west exposures. These samples were taken either from liner material completely exposed to the weather or from material half exposed and half in the waste. The samples were chosen on the basis of evidence of possible degradation, such as embrittlement, tautness, and any other indications of anomalies in the liner.
- Samples representing a vertical cross-section of the lagoon from the top edge to the bottom. Samples were taken from the berm, from the slope, and from the bottom. The berm samples were primarily weather-exposed. The slope samples were taken from the upper waste zone, where the waste is saturated. Figure 2 shows an idealized cross-section of the lagoon.
- Samples with field and/or factory seams.

TESTING

The following samples were selected for testing:

Sample 1 - Upper and lower halves.
Sample 3 - Upper half.
Sample 4 - Upper and lower halves.
Sample 5 - Seamed area.
Sample 6 - Upper half.
Sample 7 - Seamed area.
Sample 11 - Seamed area.
Sample 12 - Upper and lower halves.
Sample 15 - Seamed area.
Sample 17 - Seamed area.

Standard tests were used to characterize the PVC liner samples (3). The samples were removed from their sealed bags and physically tested on an "as received" basis. Physical testing included tensile strength (ASTM D412), tear strength (ASTM D624), puncture resistance (Federal Test Method Standard No. 101B, Method 2065), and hardness (ASTM D2240). Grain direction of all samples was determined by heating marked discs; shrinkage occurs in the machine direction. Where available, seams were tested in shear (ASTM D816) and in peel (ASTM D1876). Volatiles were removed from the samples in two steps. First, moisture was removed by placing samples over calcium chloride ($CaCl_2$) in a desiccator at 50°C for 4 days. Then the samples were heated at 105°C for 4 to 20 hr with a 2:1 carbon tetrachloride (CCl_4): methanol (CH_3OH) solution. Ash (ASTM D297) was also run on devolatilized samples.

RESULTS

Results of the testing are summarized

TABLE 2. FIELD OBSERVATIONS OF LINER SAMPLES

Sample	Location in lagoon	Seams	Condition of Samples
1	North side of lagoon Upper half weather-exposed Lower half exposed to unsaturated sludge	Factory seam in both halves	Upper half cracked, brittle Lower half supple
2	West side of lagoon, northern corner Upper half weather-exposed Lower half exposed to unsaturated sludge	Factory seam in upper half	Upper half brittle, ripped, shows discoloration Lower half supple
3	West side of lagoon Upper half weather-exposed Lower half exposed to unsaturated sludge	Factory seam in upper half	Upper half brittle, cracked, grass growing through hole in liner Lower half is supple
4	South side of lagoon Upper half weather-exposed Lower half exposed to unsaturated sludge	Factory seam in both halves Unadhered field seam in upper half Intact field seam in lower half	Upper half brittle, cracked Lower half supple
5	East side of lagoon Completely exposed to weather	Factory seam	Discolored, supple
6	East side of lagoon Upper half weather-exposed Lower half exposed to unsaturated sludge	Factory seam in upper half	Upper half brittle, cracked Lower half supple
7	East side of lagoon near lagoon bottom Completely under saturated sludge	No seam	Dimpled, overlies hydrogen-sulfide-smelling, peat-like black soil
8	Bottom sample from southern end of lagoon	No seam	Dimpled, supple
9	East side of lagoon near lagoon bottom Completely under saturated sludge	No seam	Dimpled, supple, overlies similar peat-like black soil as #7
10	South side of lagoon near lagoon bottom Completely under saturated sludge	No seam	Two creases in sample, underlain by similar peat-like black soil as #7
11	Under north berm-folded portion Exposed to soil, same possible exposure to sludge	Factory seam	Dry, fairly stiff
12	North side of lagoon on slope Upper half in unsaturated sludge Lower half in saturated sludge	Factory seam in upper half	Lower half dimpled, supple
13	North side of lagoon on slope Completely under saturated sludge	No seam	Dimpled, supple
14	Bottom samples from lagoon center		Dimpled, supple
15		Factory seam in #15	
16	Bottom samples from northern end of lagoon		Dimpled, supple
17		Factory seam in #17	
18	Sample adjacent to #11	No seam	Dry, fairly stiff

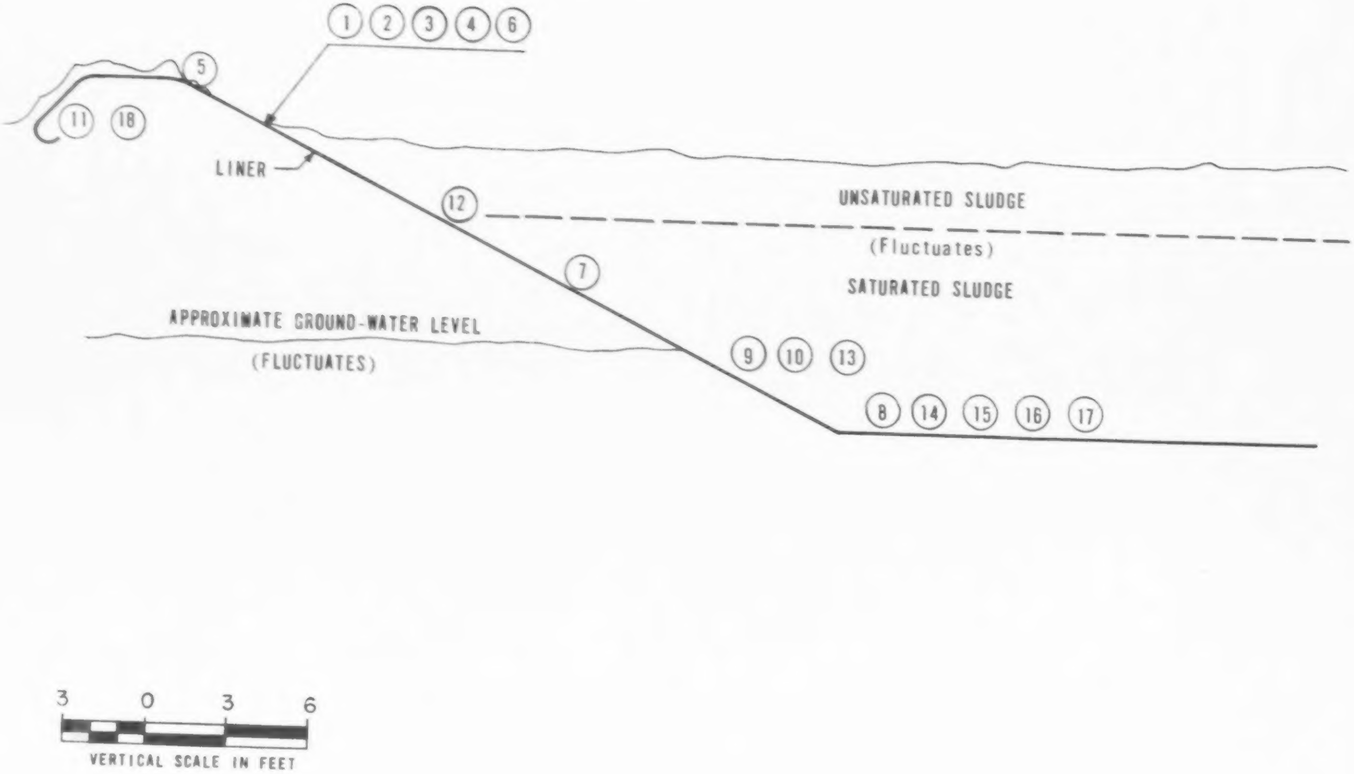
① ② ③ ④ ⑥
⑤
⑪ ⑱
LINER
⑫
UNSATURATED SLUDGE
(Fluctuates)
⑦
SATURATED SLUDGE
APPROXIMATE GROUND-WATER LEVEL
(FLUCTUATES)
⑨ ⑩ ⑬
⑧ ⑭ ⑮ ⑯ ⑰
3 0 3 6
VERTICAL SCALE IN FEET

Figure 2 (See figure legends list)

in three tables. Table 3 presents data on the samples exposed to the weather arranged in order of decreasing exposure severity--i.e., south-facing exposure being most severe, followed by west-facing, then east-facing, with north-facing exposure being the least severe. In Table 4, the data are presented in a vertical cross-section arranged from the top of the lagoon to the bottom. Table 5 contains data on all the seam testing.

DISCUSSION

WEATHER-EXPOSED SAMPLES

Samples of the liner exposed to weathering were generally brittle and dry. During the sample collection, the brittleness was evident through cracking and splitting of the membrane. However, it was possible to roll up the liner samples, possibly because of the warm weather. Localized shrinkage of the liner had occurred, as evidenced visually by its tautness. Tensile test specimens from the top of sample 1 cracked along the edges as they were died out. An attempt was made to avoid the cracks by dieing specimens from a warmed sample, but these also cracked. Tensile and tear strength values reflect this brittleness.

The brittleness of the weather-exposed samples, probably resulting from the loss of plasticizer, is shown by low values for extractables and elongation at break and high hardness values (see Figures 3 through 5). Only sample 5 , which was taken near the discharge pipe, was not brittle. Sample 6, located adjacent to sample 5, was brittle and is a better example of west-facing exposure. The arrangement of samples on Table 5 (with the exception of sample 11), from expected worst conditions to mildest, holds true for the test values. Sample 5 is not considered to be representative of a weather-exposed sample because of exposure to newly discharged material.

SLUDGE-EXPOSED SAMPLES

Liner samples from the main body of the lagoon were exposed to:

- Saturated sludge on the bottom.
- Intermittent cycles of saturated and unsaturated sludge on the slopes when the liquid level within the sludge fluctuated.
- Intermittent cycles of weather and sludge at the waste/weather interface at the top of the slope.

During the sample collection, it was noted that the liner material in the samples exposed to saturated waste showed an imprint of the underlying soil and some swelling, whereas samples exposed to unsaturated waste were flat. Samples taken on the lower portion of the slopes at the southern end of the lagoon were underlain by black, peak-like granular soil with a hydrogen sulfide odor.

The uppermost liner samples on the lagoon slope at the waste/weather interface intermittently exposed to sludge (the lower portion of samples 1 and 4) showed similar properties to those of the liner sample exposed to the soil (sample 11). These two waste/weather samples had the lowest extractables content and elongation at break values and the highest S-100 values of all sludge-exposed samples. Volatiles for these samples (1 and 4) were 5.10% and 3.14% water and 1.41% and 0.52% organic volatiles after 20 hr at 105°C, respectively (Figures 3 through 5).

Samples tested from lower on the lagoon slope, which were exposed to saturated or unsaturated sludge, had similar properties (Table 4). The volatiles content of these latter samples was higher than those of the weather-exposed samples, ranging from 5.60% to 8.62% water, and from 1.54% to 1.96% organic volatiles. They had lower hardness values (see Table 4), lower S-100 values, and higher elongation at break values than the weather-exposed samples (Figures 4 and 5).

The two samples from different locations on the lagoon bottom (samples 15 and 17) had similar water contents--3.42% and 2.49%, respectively--and their organic volatiles measured 0.85% and 0.94%, respectively. The samples had equal hardness. These samples had the highest extractables and the lowest hardness of all tested samples.

SOIL-EXPOSED SAMPLE

The soil-exposed sample (sample 11) was collected as a possible control. Because of the nature of the cleaning opera-

TABLE 3. WEATHERED SAMPLES OF PVC LINER FOR CALCIUM SULFATE SLUDGE LAGOON

Item	Sample number					
	11	1 Upper	6 Upper	5	3 Upper	4 Upper
Lagoon location Exposure conditions	N-side Undersoil	N-side/s-facing Weather	E-side/w-facing Weather	E-side/w-facing Weather	W-side/e-facing Weather	S-side/N-facing Weather
Average thickness, mils	18.8	16.0	15.6	19.3	16.0	18.2
Analytical properties:						
Volatiles, % over desiccant (ar)[a]	0.75	1.37	3.68	1.04	4.26	1.56
At 105°C 20 hr (ar)	0.34	1.78	0.28[b]	2.18	0.92	0.72
Extractables, % (db)	26.50	18.91	20.23	30.52	20.54	21.91
Ash, % (db)	7.54	8.19	----	6.45	7.50	8.41
Physical properties (ar):[c]						
Tensile at break, psi:						
Machine	2,940	2,430	2,500	3,310	3,390	2,925
Transverse	3,135	3,015	2,470	3,205	3,155	2,795
Elongation at break, %:						
Machine	260	5	25	205	80	115
Transverse	285	25	20	225	55	70
Tensile set, %:						
Machine	165	1	20	125	50	90
Transverse	165	15	3	130	50	50
S-100, psi:						
Machine	2,345	----	----	2,810	----	2,895
Transverse	2,280	----	----	2,585	----	2,645
S-200, psi:						
Machine	2,700	----	----	3,240	----	----
Transverse	2,715	----	----	3,405	----	----
Tear strength, ppi:						
Machine	535	235	295	560	515	595
Transverse	580	170	327	495	355	430
Puncture resistance:						
Gage, mils	19.8	16.7	16.8	18.3	17.4	16.0
Stress, lb	37.6	9.2	16.2	33.1	25.2	26.4
Elongation, in.	0.44	0.20	0.35	0.42	0.26	0.28
Hardness, shore D						
5-sec reading	42	53	54	42	52	51

[a] ar = as received; db = dry basis.

[b] At 105° for 4 hr.

[c] Tests performed on samples as received.

TABLE 4. ANALYSIS OF SAMPLES FROM A VERTICAL CROSS-SECTION OF PVC LINER FOR CALCIUM SULFATE SLUDGE LAGOON

Item	Sample number								
	11	1 Upper	1 Lower	4 Lower	12 Upper	12 Lower	7	15	17
Lagoon location	N-side	N-side	N-side	S-side	N-side	N-side	W-side	Center	N-end
Exposure conditions	Undersoil	Weather	Weather/waste interface	Weather/waste interface	Unsaturated waste	Saturated waste	Saturated waste	Lagoon bottom	Lagoon bottom
Average thickness, mils	18.8	16.0	20.3	20.8	21.2	21.6	20.4	19.8	20.7
Analytical properties:									
Volatiles, % over desiccant (ar)[a]	0.75	1.37	5.10	3.14	8.62	8.27	5.60	3.42	2.49
At 105°C 20 hr (ar)	0.34	1.78	1.41	0.52	1.96	1.60	1.54	0.85[b]	0.94
Extractables, % (db)	26.50	18.91	21.50	26.10	31.02	32.71	32.44	34.98	35.15
Ash, % (db)	7.54	8.19	7.90	9.32	6.89	6.67	7.13	7.08	6.69
Physical properties:[c]									
Tensile at break, psi:									
Machine	2,940	2,430	2,915	2,780	2,610	2,505	2,605	2,460	2,760
Transverse	3,135	3,015	2,575	2,495	2,315	2,335	2,440	2,320	2,550
Elongation at break, %:									
Machine	260	5	220	275	300	295	280	310	265
Transverse	285	25	220	295	310	330	300	315	290
Tensile set, %:									
Machine	165	1	125	105	95	70	85	70	60
Transverse	165	15	110	130	100	90	90	80	70
S-100, psi:									
Machine	2,345	----	2,350	1,885	1,635	1,500	1,740	1,265	1,625
Transverse	2,280	----	2,090	1,720	1,340	1,205	1,580	1,245	1,415
S-200, psi:									
Machine	2,700	----	2,830	2,350	2,105	2,010	2,210	1,805	2,280
Transverse	2,715	----	2,460	2,065	1,750	1,630	2,010	1,700	1,975
Tear strength, ppi:									
Machine	535	235	520	495	345	330	380	260	325
Transverse	580	170	355	415	330	310	360	270	295
Puncture resistance:									
Gage, mils	19.8	16.7	20.4	21.1	21.2	21.6	20.2	19.7	20.5
Stress, lb	37.6	9.2	31.6	40.1	35.2	32.3	31.8	26.1	32.6
Elongation, in.	0.44	0.20	0.33	0.64	0.66	0.71	0.63	0.69	0.67
Hardness, shore D									
5-sec reading	42	53	51	36	32	29	34	28	28

[a] ar = as received; db = dry basis.

[b] At 105° for 4 hr.

[c] Tests performed on samples as received.

TABLE 5. DATA ON SEAMS IN PVC LINER FOR CALCIUM SULFATE SLUDGE LAGOON

Item	Sample number										
	1-Upper	1-Lower	3-Upper	4-Upper	4-Lower	5	7	11	12-Upper	15	17
Exposure conditions	Weather	Weather/waste interface	Weather	Weather/waste interface	Weather/waste interface	Weather	Saturated waste	Soil	Unsaturated waste	Bottom	Bottom
Breaking factor, ppi transverse	48.3	49.7	52.1	51.7	52.5	62.0	49.4	54.3	48.7	45.6	52.4
Factory seam strength:											
Shear, ppi	43.9	46.8	40.3	38.4	44.2	51.8	44.8	53.8	47.2	40.0	43.7
Locus of failure	SE-BRK[a]	SE-BRK	SE	SE	SE	SE	SE	SE	SE	SE	SE
% of breaking factor	91	94	77	74	84	84	91	99	97	88	83
Factory seam strength:											
Peel, ppi	27.0	21.3	26.1	25.5	25.0	26.6	21.1	25.8	23.5	17.7	20.7
Locus of failure	AD	AD	AD	AD	AD	AD	AD	AD	AD	AD	AD
Field seam strength:											
Shear, ppi	----	----	----	----	45.9	----	----	----	----	----	----
Locus of failure	----	----	----	----	SE-AD	----	----	----	----	----	----
% of breaking factor	----	----	----	----	87	----	----	----	----	----	----
Field seam strength:											
Peel, ppi	----	----	----	----	13.0	----	----	----	----	----	----
Locus of failure	----	----	----	----	AD	----	----	----	----	----	----

[a] SE = failure at seam edge; AD = failure in seam adhesion; SE-BRK = failure at either seam edge or in liner; SE-AD = failure at either seam edge or in seam adhesion.

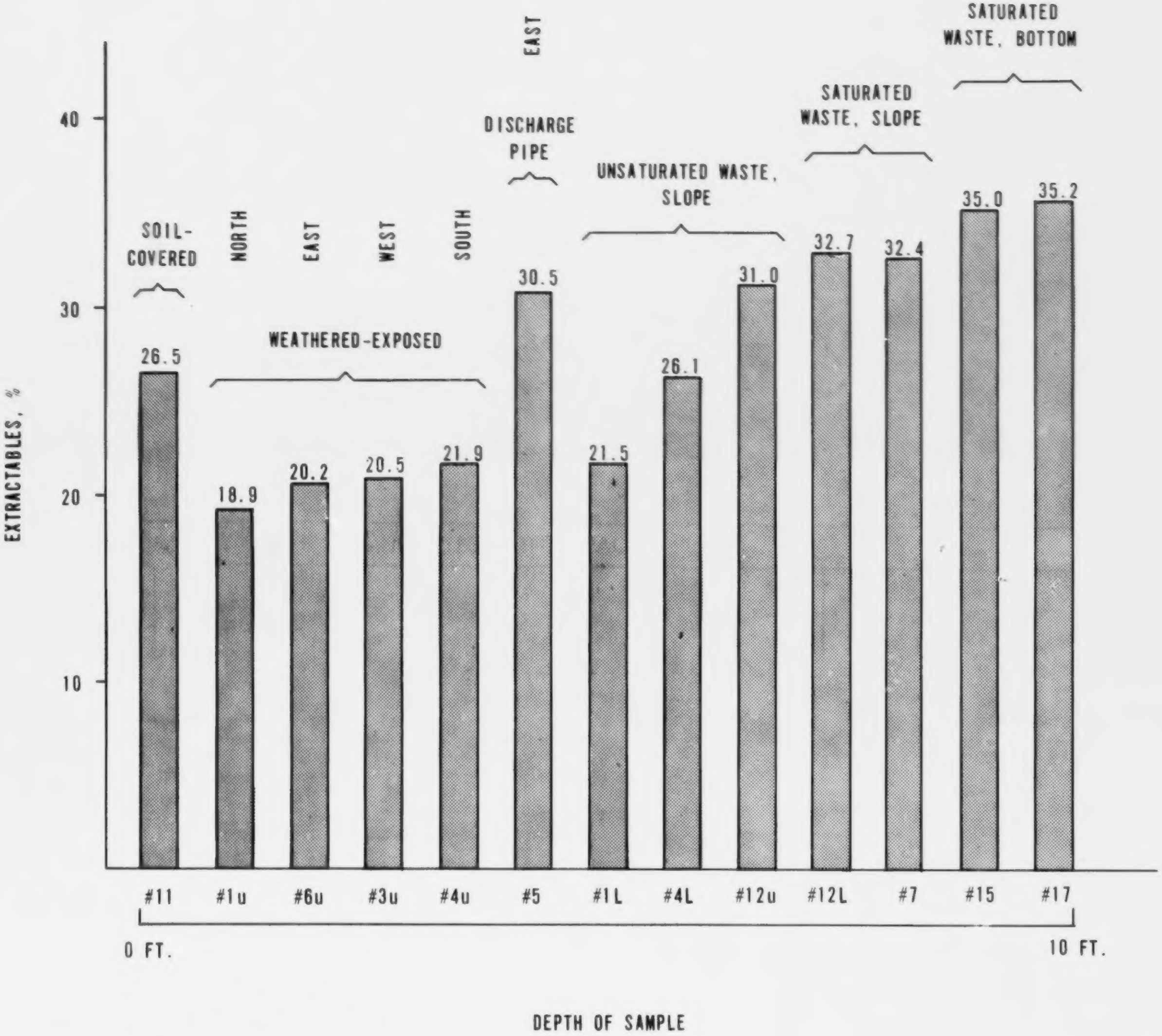

Figure 3 (See figure legends list)

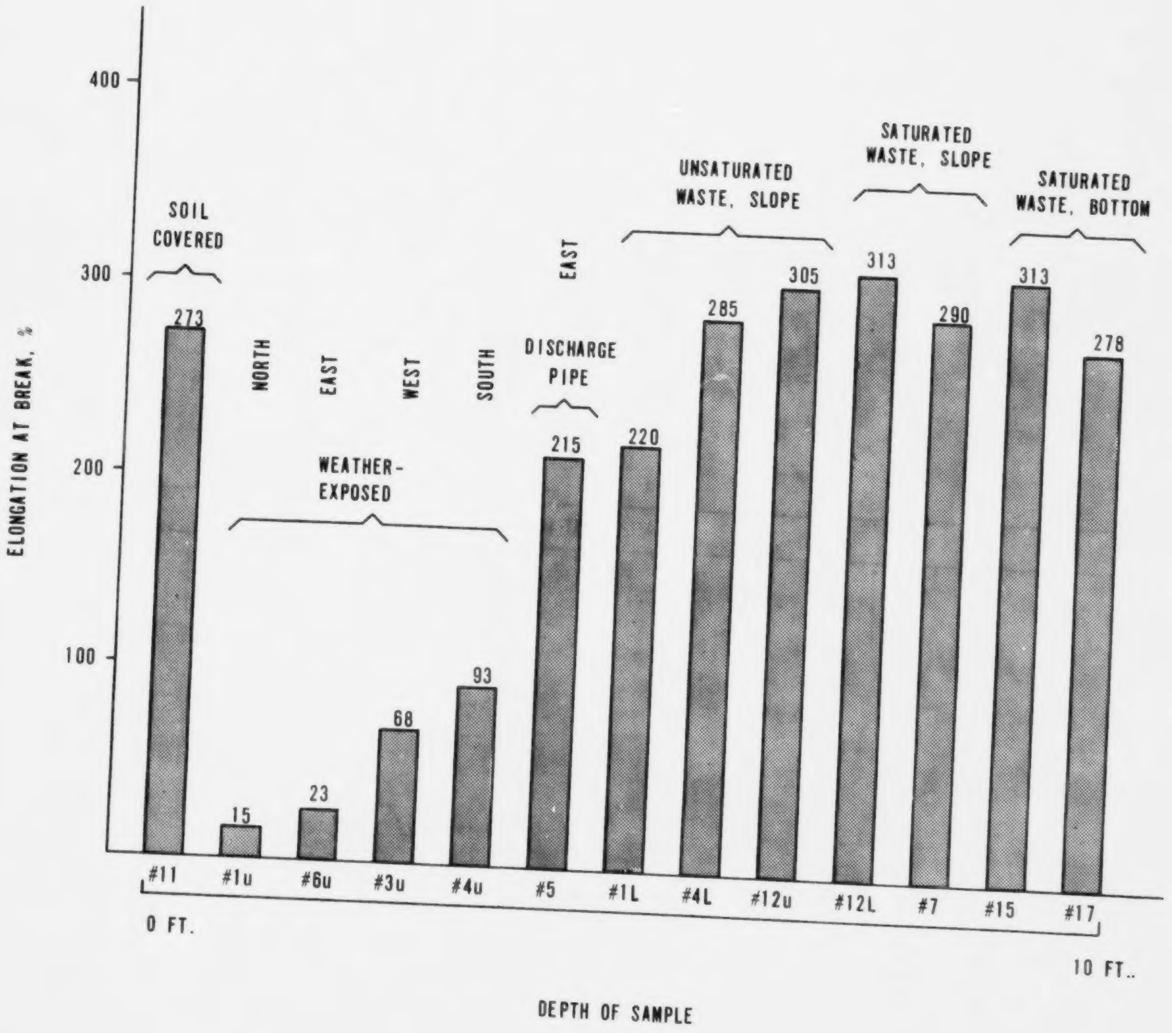

Figure 4 (See figure legends list)

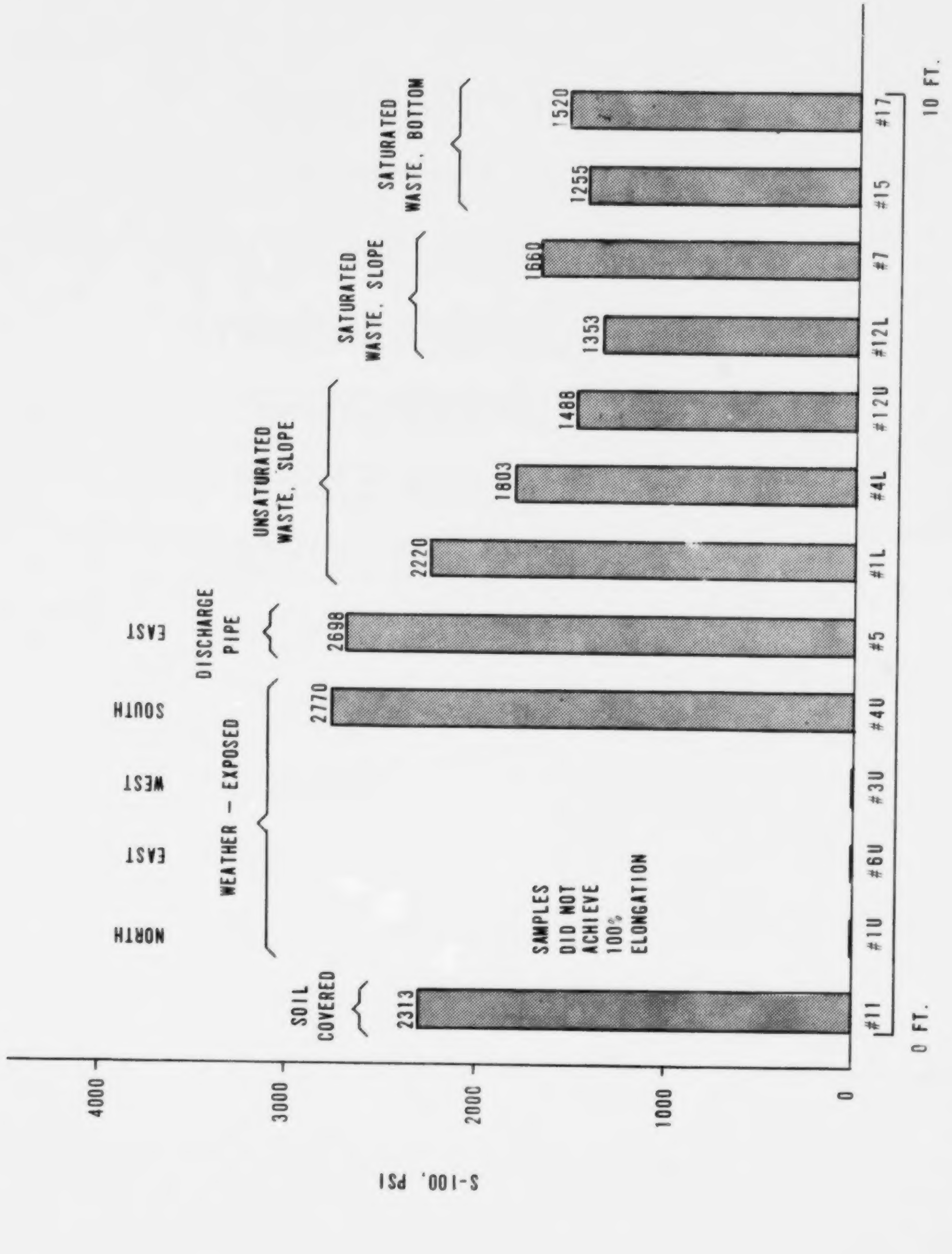

Figure 5 (See figure legends list)

tions at the lagoon, however, the sample may have been exposed at some point to the weather and possibly to the sludge. The low extractables content and high modulus values (S-100) indicate that the sample is likely to have undergone moderately severe exposure conditions; therefore it could not be used as a control.

SEAMS

Factory seam samples from different levels in the lagoon and one sample of the field seam were collected. All seams appear to have been made with a bodied solvent. The factory seams are approximately 1 in. wide and the field seam approximately 2 in. wide. All seams appear to have been made in the machine direction; thus testing across the seam constitutes a transverse direction test with respect to the sheeting. All factory seams were observed to be in good condition. Seam strength tested in shear of the factory seams generally was good, ranging from 74% to 99% of the breaking strength of the liner material. The brittle, weathered samples and the samples from the bottom of the lagoon had the lowest seam strength in shear; the sample exposed mainly to soil (No. 11) had the best strength. All of the seams tested in peel failed in the adhesive or "glue line." The seams peeled apart, leaving traces of bodied solvent on both sides. The lowest peel strength, 17.7 ppi, was measured in samples from the bottom of the lagoon. The highest, 27.0 ppi, was from a weather-exposed sample.

The field seam collected had a section that had not been properly bonded. This appeared to be a "holiday" or unbonded section. The bonded section showed good shear strength at 87% of the breaking strength of the material. This is higher than the factory seam shear strength for the same sample, but it does not take seam width into account. The peel strength, however, was low at 13.0 ppi, which is approximately half the peel strength of the factory seam.

CONCLUSIONS

1. Results from field testing confirm previous laboratory and pilot-scale studies. Properties of PVC liner samples from a sludge lagoon vary considerably, depending on sample location, and the condition of samples reflects the degree to which they are waste- or weather-exposed. However, neither the properties nor their variability were unexpected in light of results from previous laboratory testing (4).

2. Exposure to the weather was the most significant source of degradation of the liner. The sample on the north side (south-facing) showed the most severe effects. Samples of the liner under the sludge, which underwent minimal or no exposure to the weather (saturated sludge and lagoon bottom samples), showed normal properties for PVC liners. Samples exposed to the weather showed evidence of shrinking and had low values for thickness. These observations coupled with the physical deterioration indicate a loss of plasticizer. Comparing the extractables contents of the samples as an estimate of the plasticizer content with 30% (which approximates the amount normally compounded in PVC sheeting), it is clear that the weathered samples have lost plasticizer. The samples on the lagoon bottom, however, have retained plasticizer and physical properties.

3. This PVC liner, after 9 years of exposure under the waste, has comparable testing values to unexposed 20-mil PVC sheeting, according to the specifications shown in Table 6. Therefore it appears that the type of sludge being impounded did not affect the integrity of the PVC liner. However, if a retained sample of the original PVC liner were available, these results could be expressed as changes in properties as a result of exposure or percent retention of unexposed 20-mil PVC sheeting, as reported in the literature.

4. The factory seams in this liner maintained their integrity during the long-term exposure, but the field seams did not. All factory seams tested in shear failed at the seam edge or elsewhere in the sample, reflecting the strength of the liner. The field seam, however, had some failure in the seam adhesive itself as well as seam edge failure. When tested in peel, which is a more severe test, all seams failed in the glue lines. The type of seam failure in shear in the field seam and the evidence of a "holiday" indicate an inadequate seaming operation and empha-

TABLE 6. PROPERTIES OF UNEXPOSED 20-MIL PVC MEMBRANES[a] AND SAMPLES EXPOSED TO SLUDGE ON LAGOON BOTTOM

Physical properties	Unexposed membranes[a]				Exposed membranes	
	#17[b]	#19	#67	#88	#15	#17
Average thickness, mils	20	22	22	20	20	21
Tensile strength, psi:						
Machine	2,640	2,780	3,020	3,395	2,460	2,760
Transverse	2,520	2,260	2,765	2,910	2,320	2,550
Elongation at break, %:						
Machine	270	330	385	325	310	265
Transverse	290	340	415	335	315	290
Tensile set, %:						
Machine	68	97	192	102	70	60
Transverse	77	105	207	101	80	70
S-100, psi:						
Machine	1,260	1,150	1,250	1,870	1,265	1,625
Transverse	1,130	1,060	1,110	1,600	1,245	1,415
S-200, psi:						
Machine	2,080	1,890	1,820	2,610	1,805	2,280
Transverse	1,850	1,590	1,585	2,190	1,700	1,975
Tear strength (Die C), ppi:						
Machine	350	295	340	465	260	325
Transverse	315	275	295	470	270	295
Puncture resistance:						
Stress, lb	25.8	24.0	27.8	28.6	26.1	32.6
Elongation, in.	0.69	0.71	0.68	0.56	0.69	0.67
Thickness, mils	20	21	22	----	20	21
Hardness, Durometer A points 5-sec reading	76A	72A	75A	80A	72A	71A

[a] Source: Reference 5, p. 50.

[b] Liner number. Unexposed liner numbers are Matrecon inventory numbers; exposed liner numbers are sludge lagoon sample numbers.

[c] Tests performed are tensile strength, ASTM D412; tear strength, ASTM D624; puncture resistance, FTMS 101B, Method 2065; and hardness, ASTM D2240.

size how critical field seaming is to a successful lined impoundment.

5. Mechanical puncturing, inadequate protection from exposure to the weather and poor field seaming contributed to the deterioration and failure of the liner material.

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5. Haxo, H.E., R.S. Haxo, and T.F. Kellogg. Third interim report: Evaluation of liner materials exposed to leachate. EPA-600/2-79-038, U.S. Environmental Protection Agency, Cincinnati, Ohio, 1979.

FIGURES LEGEND LIST

Figure 1 - Plan view of the lagoon showing locations of sampling and the field seam. Liner made of 2 sheets seamed on the field. The sheets are folded in the corners.

Figure 2 - Idealized cross-section of lagoon showing depth at which samples were taken. Samples 1-6 were taken in August 1982 and Samples 7-18 in September 1982.

Figure 3 - Percent extractables of exposed samples arranged in approproximate order from lagoon top to bottom. Weather-exposed samples are arranged in decreasing severity from south facing to west, east, then north facing.

Figure 4 - Percent elongation at break values for exposed samples arranged in approximate order from lagoon top to bottom. Weather-exposed samples are arranged in decreasing severity from south facing to west, east, then north facing. Data are the averages of values obtained in machine and transverse directions.

Figure 5 - Stress at 100% elongation in psi for exposed samples arranged in approximate order from lagoon top to bottom. Weather-exposed samples are arranged in decreasing severity from south facing to west, east, then north facing. Data are the averages for values obtained in machine and transverse directions.

EVALUATIONS OF TIME-DOMAIN REFLECTOMETRY AND ACOUSTIC EMISSION TECHNIQUES TO DETECT AND LOCATE LEAKS IN WASTE POND LINERS

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ABSTRACT

There is a great need to find reliable, non-destructive monitoring techniques to determine if a significant leak exists in hazardous waste impoundment liners before the leachate seriously damages the groundwater regime. There is also a need to find techniques that can economically locate precisely the area where a leak is occurring in the liner material.

The phase one part of this contract identified and evaluated a wide range of techniques that might be applied to leak detection in waste impoundment liners (Waller and Davis, 1981). Two of the techniques recommended for immediate further study and evaluation were acoustic emission monitoring and time-domain reflectometry.

This paper describes the laboratory and field studies carried out by EarthTech Research Corporation to evaluate the potential usefulness of acoustic emission monitoring and time-domain reflectometry for detecting and locating leaks from waste pond liners.

The acoustic emission monitoring experiments showed that acoustic sounds, at frequencies up to 500 Hz, are emitted when water flows turbulently at rates between 0.3 and 1 cm/sec through a sand and pea gravel. Turbulent flow may occur in the sand at flow rates down to 0.1 cm/sec. The amplitude of the acoustic sounds is 100 times greater than the ambient background noise level that is likely to occur at a liquid impoundment pond. The acoustic sounds, at a frequency of 450 Hz, have an attenuation of 0.5 dB/m at a depth of one meter in a lake. Using the existing equipment we might detect and determine the location of leaks with a flow rate of 1 cm/sec at a range of about 3 m from a leak.

The time-domain reflectometry experiments showed that a leak with dimensions equal to or larger than 0.5 the spacing between the parallel transmission line conductors can be detected by this technique. The maximum conductor spacing tested was 2 m, but larger spacings between the conductors are feasible.

Further tests in the field under controlled leak conditions are necessary to determine the potential of both the acoustic emission monitoring and the time-domain reflectometry techniques for detecting and locating leaks in a waste pond liners.

INTRODUCTION

Historically the groundwater in this country has been considered to be too plentiful to be damaged by man. Over the past decade, the groundwater has been increasingly threatened by poor management practices both in its removal for industrial and agricultural use and by a lack of control over waste disposal practices. Contaminants that leak from waste disposal sites percolate into the groundwater and eventually into our water-supply reservoirs. Federal regulations over the past ten years have resulted in the reduction of waste discharge into surface waters, but the land has become a major depository of hazardous waste materials.

Each year at least 35 million metric tons of hazardous wastes are put into impoundments lined with natural or man-made materials. The liners act as barriers to the movement of the hazardous materials out of the site into the groundwater, but there is little evidence at present as to the effectiveness of the different liner materials as barriers. At present we monitor the groundwater quality from wells placed hydrologically down stream. Thus the hazardous materials must be in the groundwater before they are detected. It is clear that significant damage to the groundwater may occur before the waste materials are detected.

At present there are no proven methods that can determine the source of a leak in a liner before it reaches the groundwater. There is a great need to find reliable non-destructive monitoring techniques to determine if a significant leak exists in an impoundment liner before the leachate seriously damages the groundwater regime. There is also a need to find techniques that can economically locate the area precisely where a leak is occurring in the liner material.

The Phase One part of this EPA contract identified and evaluated a wide range of techniques that might be applied to leak detection in waste impoundment liners (Waller and Davis, 1981). Two of the techniques that were recommended for immediate further study and evaluation were acoustic emission monitoring and time-domain reflectometry.

ACOUSTIC EMISSION MONITORING

Acoustic emission monitoring (AEM) techniques have been used for at least 50 years to evaluate stresses in rocks and metals and also to monitor earthquakes around the earth. Its application to soil structures is more recent and especially for monitoring fluid flow through soils. The technique has been used to measure turbulent flow of water through earth dams as reported by Esmiol (1971), the Bureau of Reclamation (1971), Crook and Coxen (1976), and Koerner et al. (1981).

Koerner et al. (1981) have carried out experiments in the laboratory showing that water flowing through soils does emit sound waves. We also reported similar findings at last year's symposium. We feel that sounds are emitted when water flows turbulently through soils. Normally, turbulent flow does not occur when water flows through soils, but if there is a sufficient head or potential, as in a liquid waste impoundment site, non-Darcian flow in a permeable soil can occur. Thus acoustic emission monitoring techniques might have application for detecting the source of a leak from a waste impoundment site. Possible rapid attenuation of the sounds produced by the leachate flowing through the soils and high ambient background noise levels will make the AEM technique impractical in a solid waste site. It may be practical, however, in a liquid impoundment site where a leak of hazardous materials is potentially much more hazardous.

The objectives of the acoustic emission monitoring aspect of this project are to determine the spectral characteristics of the sounds emitted when water flows at different rates through different soils. The attenuation rates of these sounds in different materials are also to be determined.

TIME-DOMAIN REFLECTOMETRY

Time-Domain Reflectometry (TDR) is less well-known and certainly more recent than acoustic emission monitoring. Time-domain reflectometry is a wide-frequency bandwidth short-pulse length measurement technique that is sensitive to the high frequency (10^6 to 10^9 Hz) electrical properties of the materials in and around the conductors of a parallel transmission line. Typically, the TDR technique has been used by electrical and communication engineers to determine the condition of their transmission lines and the location of any faults in the lines.

Over the past decade the TDR technique has been shown to have practical application for measuring and monitoring the volumetric water content in soils independant of soil type, density, and temperature (Topp, Davis and Annan, 1981 and 1982 [a] and [b]). The high frequency electrical properties of liquid water are about twenty times greater than the electrical properties of dry geologic materials. The Phase II, Part 2, report to EPA reviews the TDR technique as applied to geologic materials.

Leak materials from waste impoundment site liners, in the soil below, are likely to have different electrical properties than those of the host soil material. TDR can measure the electrical property variations in the material along a transmission line and thus the TDR technique offers significant potential of detecting leaks from waste dump sites that have transmission lines placed under the liner.

The TDR technique is similar to the better known DC grid technique in that wires must be placed under the liner, but that is the extent of the similarity. The DC grid technique requires wires to be laid in a cross-grid under the liner. The leachate must corrode the wires and thus break an electric circuit before detection occurs. Two wires running perpendicular must be corroded before the location of the leak can be determined. The TDR technique only requires that parallel wires in one direction be placed under the liner. The TDR system actually detects the leachate between the wires and not just at the wires. If a wire should happen to break, then the TDR system can still be used whereas this is not the case in the DC grid system. Advantages of the DC grid technique compared to the TDR technique are that longer lengths of wires can be used and the instrumentation is less complex. These advantages occur at the cost of much less information.

The objectives of the TDR aspect of this project are to determine the size of an anomaly that simulates a leachate in a soil that can be detected as the transmission line conductor spacing is varied.

This paper will briefly describe the method we used to determine the potential usefulness of the acoustic emission monitoring and time-domain reflectometry for detecting leaks from waste impoundment site liners before the leachate reaches the groundwater. The results of the experiments will be given and discussed and then conclusions will be drawn and recommendations offered on each technique. The AEM experiments will be discussed first and the TDR experiments next.

AEM - EXPERIMENTAL METHOD

The laboratory experiments were designed to determine the amplitude and frequency characteristics of sounds produced when water flows at different rates through soils. The test arrangement as shown schematically in Figure 1 consisted of a 4 m polyvinylchloride (PVC) duct with a diameter of 30 cm in which water could flow at different rates through different soils at various lengths. A piezoelectric hydrophone was placed in the soil and the sounds caused by the water flowing through the soil were amplified, filtered, processed and displayed, as shown in Figure 2. A digital spectrum analyzer capable of carrying out a fast Fourier transform was used to process the data and display the amplitude and frequency characteristics of the sounds.

A great number of tests were carried out to determine the spectral characteristics of the equipment and the noise produced when water flows at different rates through the apparatus having no soil. Great care was also taken to reduce any unwanted sounds from all sources other than from the water flowing through the soil itself. The methods used are discussed in the Phase II, Part 1, report submitted to EPA September, 1982.

Experiments were also carried out to determine the attenuation of sounds over the frequency spectrum observed in the laboratory experiments. Most of the attenuation measurements were carried out in the field, either in a lake or in soils. The acoustic sensor was moved continuously away from the acoustic source, rather than being stationary. The same electronic receiving equipment was used as described above, plus an audio frequency sweep oscillator and a loud speaker were used.

Two soils were tested in the laboratory. The first was a 20/30 Ottawa sand with an average grain size of 0.7 mm. The second soil was a pea gravel in which 90 percent of sample fell between 2.5 and 5 mm, with the remaining portion between 5 and 1 mm.

The height of the soil column was varied at three levels - 70,100, and 150 cm.

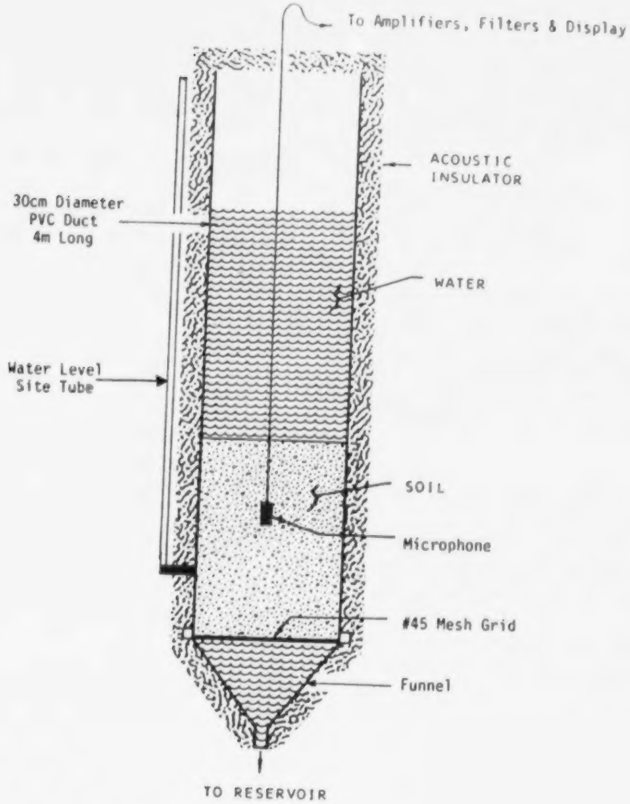
To Amplifiers, Filters & Display
ACOUSTIC INSULATOR
30cm Diameter PVC Duct 4m Long
WATER
Water Level Site Tube
SOIL
Microphone
#45 Mesh Grid
Funnel
TO RESERVOIR

Figure 1. A schematic diagram of the experimental test arrangement.

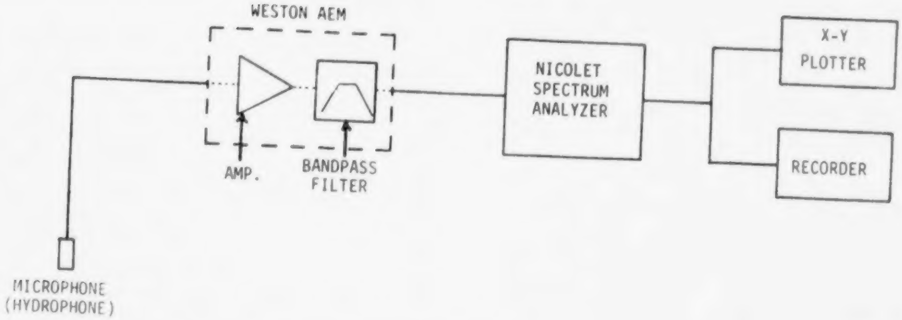
WESTON AEM
AMP.
BANDPASS FILTER
NICOLET SPECTRUM ANALYZER
X-Y PLOTTER
RECORDER
MICROPHONE (HYDROPHONE)

Figure 2. A block diagram of the electronic equipment used to detect the acoustic sounds emitted when water flows through soils.

The microphone was placed 15 cm above the bottom of the soil column in each test. The water level varied from about 3 m above the soil to just above the soil in each of the experiments, thus falling water head levels occurred during the tests. The flow velocities in the soils varied from 1 to 0.3 cm/sec which is equivalent to 10 GPM to 3 GPM in the 30 cm diameter column.

AEM - RESULTS AND DISCUSSION

Water Flow Rate Measurements

Figure 3 shows the water flow rates versus head level when there was no soil in the column and when there is sand at 70, 100 and 150 cm length in the column. The flow rates measured for each condition measured in the column were repeatable to +/-GPM.

All the flow rates are essentially linear between 10 and 4 GPM in the 30 cm diameter column. The flow through the soils is turbulent at these flow rates. The flow becomes laminar at flow rates of less than 1 GPM through the soils in the column. We, therefore, would not expect the linear response that we observe between 4 and 10 GPM on Figure 3. The reason for the observed response is that the flow rates are being primarily limited by the plumbing of the test apparatus and not by the soils in the column itself. We did not carry out a detailed analysis of the elements restricting the flow in the apparatus.

Acoustic Amplitude in Pea Gravel and Sand vs. Flow Rate

Figure 4 shows the amplitude of the sounds produced when water flows through 70 cm of pea gravel and 70 cm of uncompacted sand and 70 cm of compacted sand. The background noise amplitude when water flows through the column with no soil is also shown.

A significant portion of this background noise is produced when the water flows turbulently in the narrow section of the funnel. The flow in the open 30 cm diameter column is laminar, but the velocity increases by about 200 times in the narrow part of the funnel and the flow becomes turbulent.

We note that there is a significant increase of sound amplitude as we pass water through the pea gravel compared to uncompacted sand. Little or no significant sound is produced when water passes through the well-graded compacted sand compared to the system background noise level. We shall discuss the significance of these observations in the following paragraphs.

Source of Acoustic Sounds

The above results in the compacted and uncompacted sand lead us to postulate that the movement of the soil grains with respect to each other is the major source of acoustic sounds. In the compacted sand the grains are placed tightly together and this cannot move.

The significant noise amplitude observed when water passes through the pea gravel which has a wide variation of grain sizes also points to the above conclusion that the grains hitting each other is a major source of acoustic sounds. It seems likely that the finer grain particles are moving through the larger pore spaces set up by the larger grain particles and striking other particles.

We also note from Figure 4 that when water flows through the pea gravel or uncompacted sand the sounds fall into the background noise level at about 4 GPM in the 30 cm diameter column. This flow rate is about 2 to 4 times greater than that which we calculate to be necessary for laminar flow in the soil. It is obvious that acoustic sounds can only occur when the flow is turbulent.

Acoustic Spectra in Soils vs. Flow Rate

Figure 5 shows the spectra of the sounds emitted when water flows at different rates through the pea gravel. The frequency spectra for the compacted and uncompacted sand is essentially the same, only the amplitude is different. No sounds above the background noise level were detected at frequencies above 1 KHz up to 20 KHz. The low frequency roll-off of acoustic sounds is primarily due to the low frequency filter function of the equipment which had a cut-off frequency of about 80 Hz.

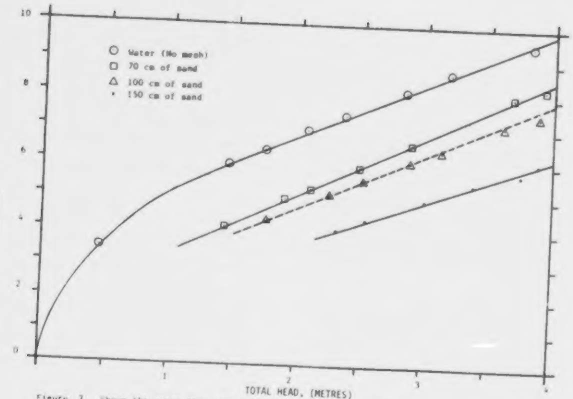

Figure 3. Shows the water flow rate through the 30 cm diameter tube at different water head levels when no soils are in the column, when different thicknesses of sand are in the column.

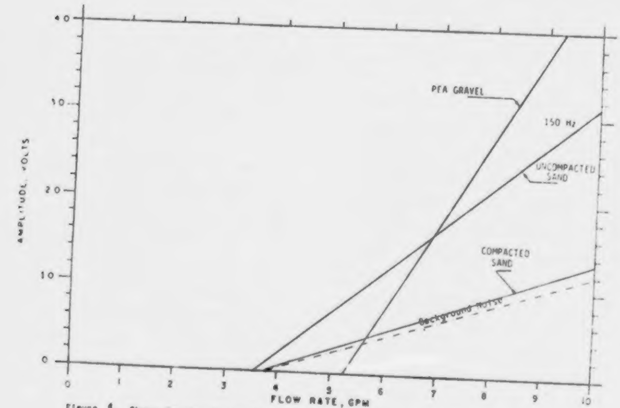

Figure 4. Shows the acoustic amplitude at 200 Hz when water flows through the 30 cm diameter tube at different rates through 70 cm of pea gravel. The amplitude response versus flow rate for the 70 cm sand and the background noise level are also shown.

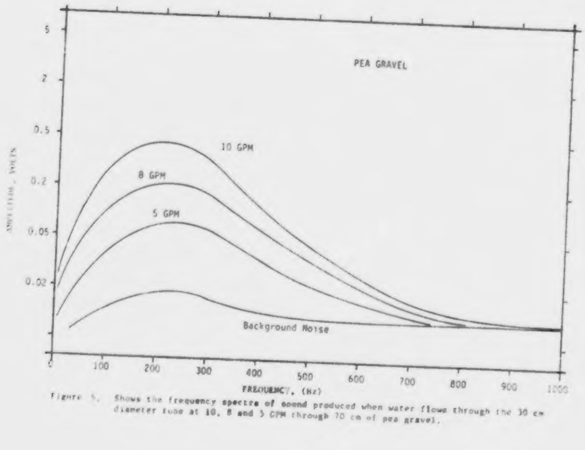

Figure 5. Shows the frequency spectra of sound produced when water flows through the 30 cm diameter tube at 10, 8 and 5 GPM through 70 cm of pea gravel.

We note from Figure 5 that most of the sound energy lies at or below 500 Hz with a peak at 200 Hz. Part of frequency response observed is due to resonant effects of the PVC column. We are primarily interested in the rate of change of amplitude of the sounds and this is a maximum at about 200 Hz. We do not have at present an explanation for this frequency response caused by water flowing through soils.

Assuming that a similar response is likely to be observed in the field means that we can reduce the bandwidth of our monitoring system and thus improve our sensitivity to the sounds produced by water flowing through the soil and reduce the amplitude of the background noise level. Simply this means that we can improve the response from our wanted signal relative to the unwanted background noise level signal.

Figure 6 shows the acoustic amplitude at 300 Hz when water flows at different rates in the 30 cm diameter column through 70, 100 and 150 cm of uncompacted sand. We note that there is a significant increase in sound amplitude as the length of the sand is increased. (This result was essentially the same at frequencies above 150 Hz for all the soils tests). In contrast there is no change in the amplitude of the sounds emitted at frequencies below 150 Hz when water flows through different lengths of sand.

It appears that as the number of sound sources increases, i.e., the height of the soil column increases, the greater the sound amplitude at the microphone. Further, this indicates that the attenuation of sounds at frequencies between 200 and 500 Hz must be low. The attenuation may increase at frequencies below 150 Hz where the amplitude of the sounds does not vary due to a significant increase in the attenuation characteristics at these frequencies. This result is not expected from our experience with seismic sounding and we have no explanation for our observations at this time.

Attenuation Measurements in Water

Attenuation measurements of sound waves were carried out in a lake. The loudspeaker which was powered by an audio frequency sweep oscillator operating at frequencies from 20 to 500 Hz was moved away from the hydrophone.

Figure 7 shows how the sound amplitude at 400 Hz decreased as the separation between the loudspeaker and the hydrophone was increased. The top line shows the response if there is no attenuation and only the decrease of amplitude due to spherical spreading is considered. The slope of the lower line shows that the attenuation in the lake water was 0.5 dB/m. This attenuation value is about five orders of magnitude greater than the attenuation value expected for sound waves at 100 Hz in water. We suspect that much of the energy is being lost at the water surface. The lake was 2 m deep and our tests were carried out at a depth of 1 m. Further, we noticed that the attenuation increased to about 1 dB/m when the tests were carried out at a depth of 0.2 m. The tests in the lake water do tend to simulate the conditions that might be found in a liquid waste impoundment site.

The background noise level observed in the lake which was located in the city of Columbia, MD, was 0.1V increasing to 0.5 V from time to time depending on the cultural activity in the area and the waves on the lake surface. The observed background noise level is about the same as that observed in the laboratory. These background noise levels should be similar to the background noise levels that will be found at a waste disposal pond site.

The results of the experiments carried out in the laboratory and in the field show that acoustic sounds can be detected at frequencies below 500 Hz when water flows at velocities of greater than 0.3 cm/sec in coarse-grained soils. The amplitude of the sounds emitted at these velocities will be equal to or greater than the background noise levels likely to be found at most field sites. The attenuation of the sounds emitted when water flows turbulently through soils was not determined explicitly in this study, but a range of up to 3 m the leak and the acoustic sensor should be possible in the field. The range may be increased with the aid of signal processing techniques such as background removal.

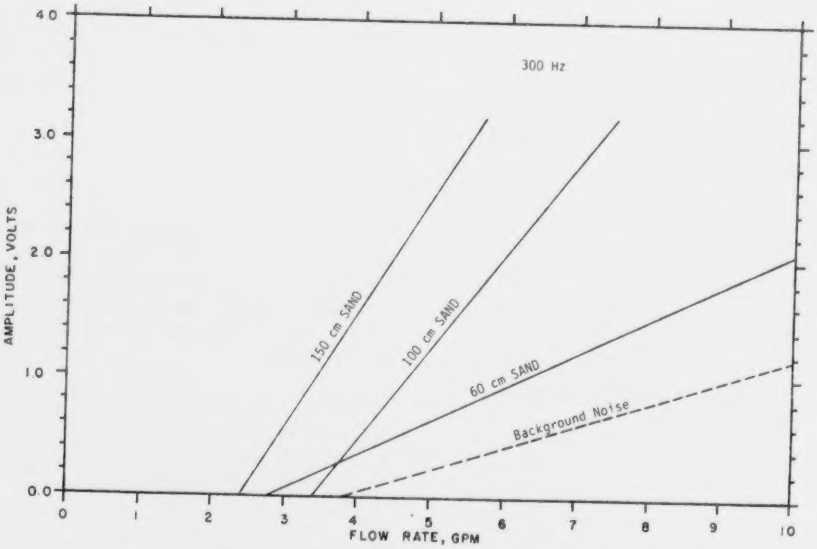

Figure 6. Shows the acoustic amplitude at 300 Hz when water flows through the 30 cm diameter tube at different rates through 70, 100 and 150 cm of sand. The background noise level is shown as a reference level.

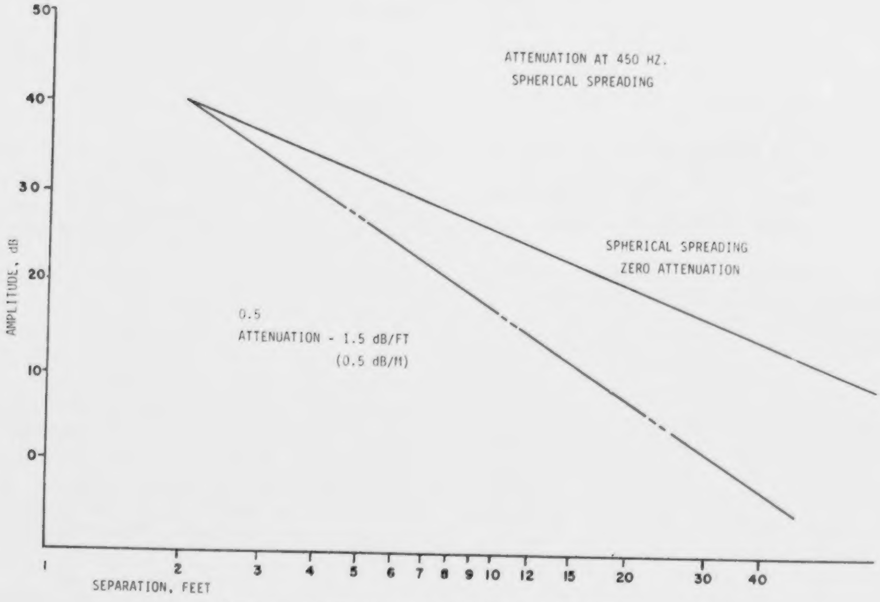

Figure 7. Attenuation of Sound in Water at 450 HZ.

AEM - CONCLUSIONS

There are a number of conclusions that can be made based on the results of this work. The most significant conclusions are that:

1. Acoustic sounds are emitted when water flows turbulently through soils,
2. The amplitude of the acoustic sounds increases as the flow rate increases,
3. The amplitude of the sounds emitted is equal to or greater than the amplitude of the background noise level likely to be found at a liquid impoundment site at a flow rate of 0.3 cm/sec.,
4. For the same flow rates the amplitude of the sounds emitted increases as the grain size variation in the soil increases,
5. For the same flow rates the amplitude of the sounds emitted decreases as the density of the soil increases,
6. There is significant power in the sounds emitted at frequencies up to 500 Hz with a peak amplitude at about 100 Hz when water flows turbulently through soils, and,
7. The attenuation of sounds at 400 Hz is 0.5 dB/m at a depth of 1 m below the water surface in a lake.

These conclusions indicate that acoustic emission monitoring of sounds is a potential method for detecting the source of a leak from a liquid waste impoundment site.

Further work is necessary to verify the usefulness of the acoustic emission monitoring technique under controlled conditions at a model pond site where leaks can be simulated and controlled. Experiments at such a pond will help us to determine the range of leak rates that can be detected acoustically and also the practical range in the pond that a leak can be detected. Tests are also necessary at the existing liquid waste impoundment pond to monitor the background noise levels at different locations over long periods of time. After these tests it should be possible to give a practical design of an acoustic emission monitoring system for detecting leaks in liquid waste impoundment ponds.

TDR - INTRODUCTION

The TDR experiments were designed to determine the size of an anomaly, simulating a leachate plume in soil that can be detected using parallel transmission lines with various spacings between the conductors.

There are many factors that affect the high frequency electrical properties of materials measured by the TDR technique. Some of these factors are:

1. The magnitude of the change of electrical properties of the anomaly compared to the host material along the transmission line,
2. The physical size of the anomaly in the transmission line,
3. The electrical loss properties of the host material in the transmission line,
4. The source power and receiver sensititivity of the TDR electronics,
5. The TDR pulse length or the pulse rise time in the case of a step pulse, and
6. The spacing of the parallel transmission line conductors.

The first three factors listed are related to the electrical properties of the materials in the ground and the last three factors are related to the TDR equipment.

It is clear that there are a number of factors interrelated to each other that affect the TDR response. In our studies to determine the usefulness of the TDR technique to detect leaks from waste site liners we can hold some of the geologic and equipment factors such as Numbers 1, 3, 4, and 5, constant and determine the TDR responses as Numbers 2 and 6, i.e., the size of the anomalies and the spacing of the conductors in the transmission line are varied.

We shall describe the experimental methods used in the laboratory and in the field to evaluate the TDR technique for detecting simulated leaks in soils. The results of the experiments will be given and discussed, and a number of conclusions will be made.

TDR - EXPERIMENTAL METHOD

A schematic diagram of the equipment used is shown in Figure 8. The electronic equipment used for these tests was a commercially available Tektronic's Model 1502 cable tester. This is a portable field unit that has a pulser with a pulse step rise time of 10^{-10} seconds, a sampling receiver with a sensitivity of $2x10^{-3}$ volts and a display unit using either an interval oscilloscope, or an internal graphic recorder or with an output for an external X-Y plotter.

The balanced parallel transmission lines used had several different types and sizes of conductors depending on the location of the experiments. The conductor material and diameter was found to have little effect on the TDR response. We wanted to determine the effect on the TDR response when the spacing between the conductors was varied. The spacing that at which we ran tests varied in increments over the range of 10 to 200 cm.

A special connector arrangement to connect the TDR unit to the conductors at the different spacings was designed to get the maximum signal transfer from the TDR unit on and off the transmission line. The connector assembly consisted of a 50 ohm to 200 ohm Balun transformer and then two metal sheets to connect the transformer to the transmission line conductors. The metal sheets were designed to provide a gradual impedance transition from the transformer to the transmission line at the different spacings.

The test setup for the transmission lines in the laboratory consisted of 6 m long, 5 cm diameter aluminum tubes being supported on a wooden frame on which the conductor spacings could be easily varied from 10 cm to 200 cm. The leaks were simulated by using boxes(15 cm)^3 filled with dry sand. The number of boxes and their position relative to the conductors could be varied.

In the field the test setup consisted of a box 2.5 x 2.5 m filled 60 cm deep with sand. The transmission line conductors were made from 1.2 cm diameter copper tubing placed at fixed spacings of 10, 20, 30, 50, 100, 150 and 200 cm. The transmission lines were placed about 45 cm below the sand surface. The leaks were simulated by adding about 1 liter of water every ten minutes. One liter of water saturates approximately a (15 cm)^3 volume of sand. The size of the anomalies used in the field were therefore similar to the boxes used in the laboratory. Both these simulations were equivalent to a leachate saturated soil in a soil host material having a volumetric water content of 20 percent.

The electrical losses in the air and in the sand were very low to the TDR pulse signal used. We feel that this arrangement was a satisfactory "first try" model of an actual field setup of a TDR leak detection system placed under a waste pond liner. We shall continue by presenting and discussing the results of the test carried out.

TDR - RESULTS AND DISCUSSION

A number of tests were carried out to determine the size of a simulated leak that could be detected as the separation between the conductors of the transmission line was varied. The first series of tests measured the effect that increasing the conductor spacing had on the TDR pulse rise time. Next we determined the change in the TDR response as the length and height of the anomaly in the transmission line was varied. Finally, we looked at the variation of the TDR response as the width and the position of the anomaly were varied within the transmission line.

TDR Pulse-Rise Time vs. Conductor Spacing

Increasing the spacing between the conductors of a parallel transmission line typically causes increased attenuation, especially to the higher frequencies in the pulse. We carried out a series of tests to determine just how the pulse-rise time increases as the transmission line conductor spacing increases. Figure 9 shows how the TDR signal response time at the open circuit end of the transmission line increases as the separation between the conductors increases. We note that the relationship is linear over conductor spacing variations of

10 to 200cm for a step pulse with an input rise time of 10^{-10} seconds, and thus having frequencies with wavelengths down to 10cm in air. The increasing pulse rise time response means that the size of an anomaly in the line must also increase. This experiment indicates that the pulse-rise time increases linearly as the conductor spacing increases over a wide range relative to the wavelengths in the signal. A similar response was observed when the transmission lines were placed in moist sand.

Physical Size of Anomaly vs. Conductor Spacing

This series of tests was carried out to determine the change to TDR response as the length of the anomaly along the transmission line and the height of the anomaly in the direction perpendicular to the plane along the conductors was varied. Figure 10 shows a plan and side views of the anomaly in the transmission line.

Figure 11 shows four TDR data responses obtained with a conductor spacing of 40 cm, and the length of the anomaly along the line is increased from 15 cm to 90 cm (1 to 6 boxes). The height and width of the anomaly was kept the same. The top TDR data trace is that observed when there is no anomaly in the transmission line. Note that as the anomaly length is increased from 15 to 30 cm, both the amplitude and time extent of the response increases. Further increase of the length of the anomaly only increases the time extent of the TDR response, and not the amplitude.

Figure 12 shows the increase of the time duration of the TDR response as the length of the anomaly is increased. The open circle line is the response observed when the height of the anomaly is equal to the spacing between the transmission line conductors and the solid dot line is the response observed when the height of the anomaly is increased to 1.5 times the line spacing. There is little variation in the TDR response when the height of the anomaly is increased. There is a significant increase in the time duration of the response as the length of the anomaly along the line increases.

It is more useful at this stage to reference the size of the anomaly to the transmission line conductor spacing, and Figure 13 shows how the TDR signal amplitude varies compared to the length relative to the line spacing. The laboratory trials are shown with a dashed line while the field trials are shown by the solid line. For the laboratory trials, the width and height of the anomaly was held equal to the conductor spacing.

Width and Position of the Anomaly in a Transmission Line

In the first series of these experiments we kept the width of the anomaly equal to the spacing between the conductors. We shall now keep the length and height of the anomaly constant relative to the spacing, and vary the width of the anomaly and the position of the anomaly relative to one of the conductors.

Figure 14 shows how the TDR signal amplitude varies as the width of the anomaly relative to the spacing varies for two cases first when the anomaly is centered between the conductors (X/S=0.5), and then when the anomaly is centered about one of the conductors (X/S=0).

We observe that the TDR signal amplitude does not decrease as rapidly when the anomaly is centered about a conductor as the signal amplitude does when the anomaly is centered between the conductors. The response is greatest when the anomaly is touching both conductors.

Figure 15 shows how the amplitude of the TDR response varies as the length of the anomaly relative to the spacing varies for anomalies that have a width equal to one-third the spacing located at different positions relative to the conductors. Once again we note a very significant decrease of the TDR signal amplitude as the boxes are moved away from a conductor. As expected, the TDR response as the length of the anomaly along the transmission line is increased is very similar to that shown in Figure 13 even though the anomaly is narrower than the conductor spacing. The tests carried out in the sandbox have similar results, and the field data is shown as a solid line on Figure 13. The agreement is quite good.

These experiments show us that the worst case for obtaining a good TDR signal

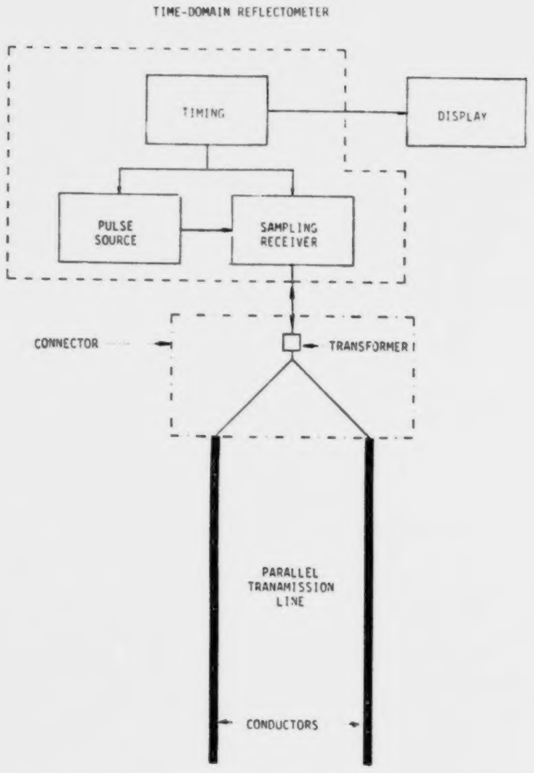
TIME-DOMAIN REFLECTOMETER
TIMING
DISPLAY
PULSE SOURCE
SAMPLING RECEIVER
CONNECTOR
TRANSFORMER
PARALLEL TRANAMISSION LINE
CONDUCTORS

Figure 8. A schematic diagram of the TDR System.

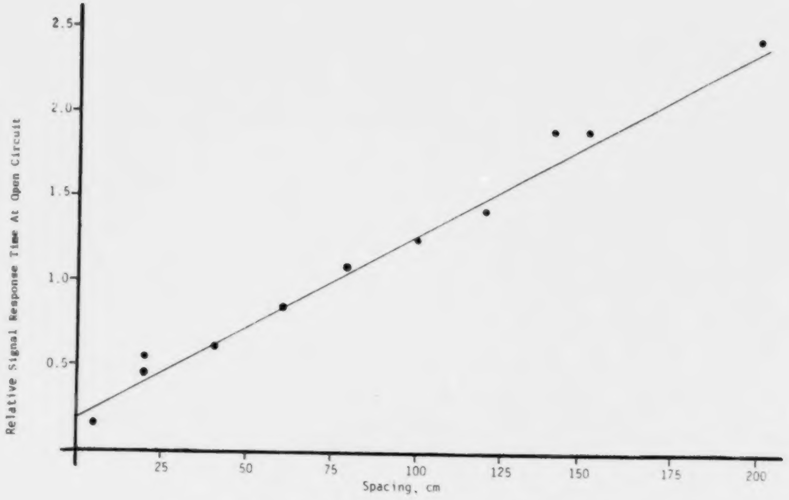

Figure 9. Shows how the relative slope of the TDR signal from an open circuit varies with spacing between the conductors of a transmission line.

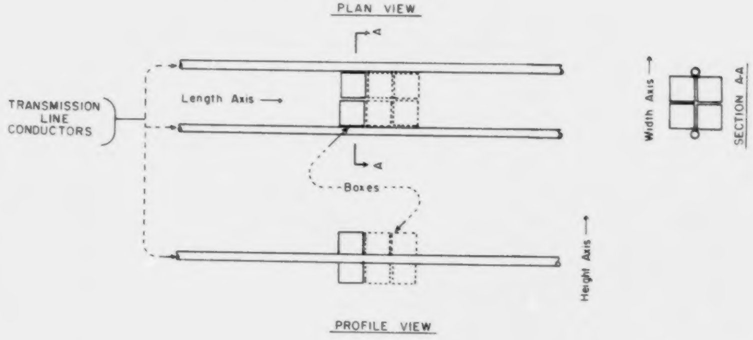
PLAN VIEW
A
A
TRANSMISSION LINE CONDUCTORS
Length Axis
Boxes
Width Axis
SECTION A-A
Height Axis
PROFILE VIEW

Figure 10. Plan and side views of the boxes filled with sand placed between the conductors of a transmission line.

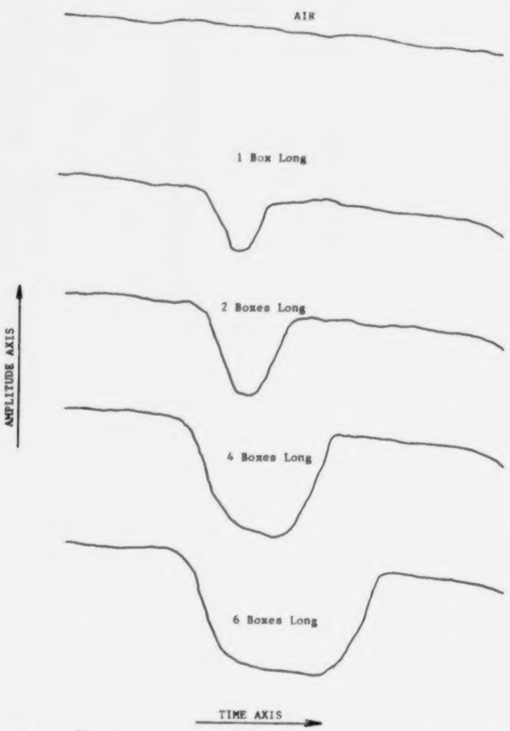

Figure 11. Shows five TDR responses. There are no boxes in the top trace and then the number of boxes along the length of the transmission is increased as shown.

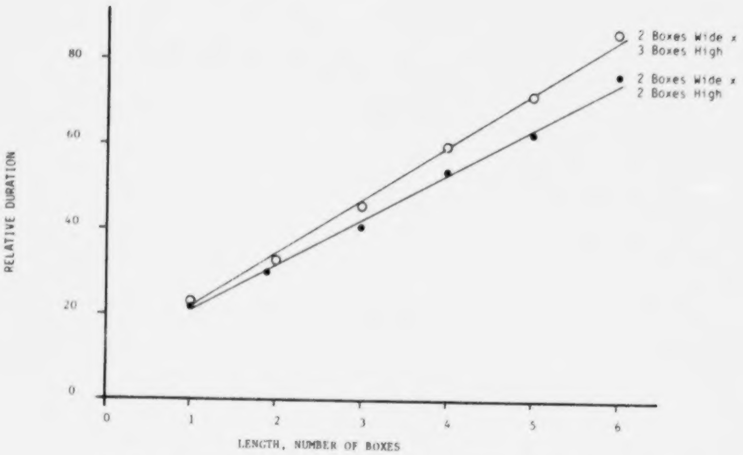

Figure 12. Shows that the TDR signal time in the anomaly increases as the number of boxes along the transmission line increases at different heights of boxes.

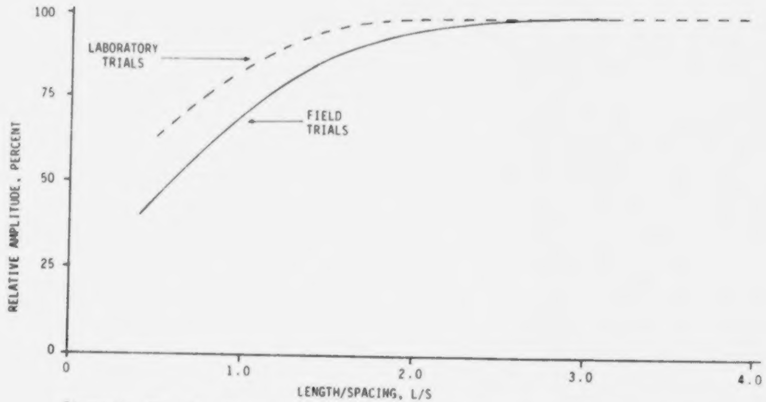

Figure 13. Shows how the amplitude of the TDR signal response varies as the length of the boxes along the line relative to the transmission line conductor spacing varies at different heights of boxes.

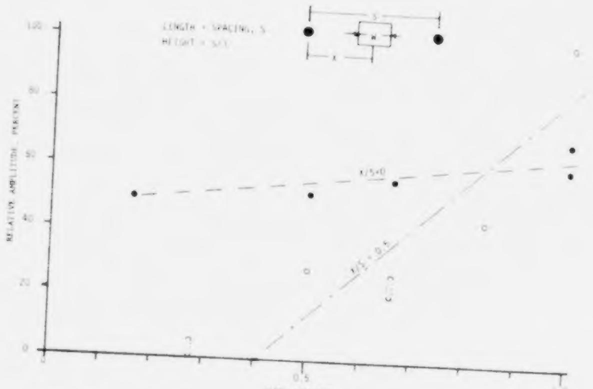

Figure 14. Shows how the TDR signal amplitude varies as the width of the boxes relative to the spacing between the conductors varies. The open circles (o) show the response when the center of the boxes are kept in the center of the conductors. The closed circles are when the boxes are centered about a conductor.

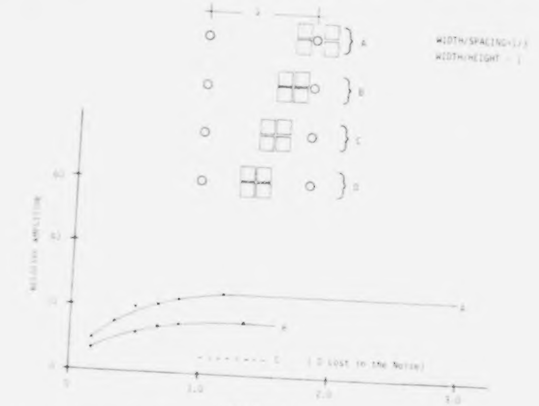

Figure 15. Shows how the TDR signal amplitude varies as the length of the boxes along the line relative to the conductor spacing varies when the boxes are at different locations in the transmission line as shown.

response is when the anomaly lies between the transmission line conductors without actually touching either conductor. This is an important observation. The TDR can detect anomalies whose dimensions are at least one-half the spacing between the conductors. The TDR signal amplitude will be equal to or greater than 20 percent the maximum signal amplitude which occurs when the transmission line penetrates an anomaly with similar electrical properties, but which is physically very large compared to the transmission line conductor spacing. It must be noted that this result is based upon the condition that the attenuation to the signals along the line are negligible. Further tests are necessary to determine the actual effect when electrical losses occur along the transmission line.

TDR - CONCLUSIONS

TDR is a versatile high resolution technique for detecting variations of electrical properties in the ground. Since the electrical properties of leachates in soils are likely to be different from the electrical properties of the soil host material, the TDR technique should be a good method for detecting small leaks from waste pond liners. There are many factors which affect the TDR response when transmission lines are placed in the ground. This study was to determine how the size of a leak that can be detected by the TDR technique varies as the spacing between the conductors of the transmission line is varied. Clearly we should like to detect very small leaks using as few transmission lines as possible at a site.

A number of conclusions can be made based on the TDR experiments carried out in this project.

1. The TDR pulse signal rise time increases as the spacing between the

conductors of the transmission line increases. In other words, the size of the leachate leak between the conductors must increase as the spacing between the conductors is increased.

2. The electrical length of the anomaly along the length of the transmission line should be equal to or greater than the TDR pulse length in the anomaly.

3. The TDR signal amplitude varies slightly as the height, i.e., the dimension whose axis is perpendicular to the plane of the conductors of the anomaly in the transmission line varies.

4. The amplitude of the TDR signal is greatest when the anomaly touches both conductors of the transmission line. The signal amplitude decreases significantly as the width of the anomaly relative to the spacing of the conductors decreases. The signal amplitude decreases less rapidly if the anomaly is touching one of the conductors.

These conclusions lead us to generalize that a cubic shaped anomaly whose sides are at least 0.5 the spacing between the conductors will have a TDR signal amplitude of about one fifth the amplitude which would occur if the transmission line penetrates an anomaly which was very large compared to the spacing of the transmission line conductors. This generalization will be affected by a number of factors that we have not included in our studies.

The electrical loss properties of the materials likely to be found in the field will reduce the TDR signal amplitude; thus the size of the anomaly will have to be increased to increase the reflected TDR signal amplitude. The electrical property contrast of the leachate saturated soil relative to that of the host soil under the waste impoundment site may not be as great as the electrical property contrast we used in our models; thus the reflected signal amplitude may not be as large in the waste site environment. Acknowledge of the electrical contrast between leachate in soils and background moisture will be necessary before a TDR system can be properly designed.

The models we used in these experiments only tested the TDR response in transmission line whose maximum spacing between the conductors was two meters. Larger spacings between the conductors are possible using the same TDR unit. Experiments to determine the maximum spacing of the conductors still need to be carried out. We need to test the TDR system using a series of different spacings between the conductors of the transmission lines placed in a sandy soil under a lined pond filled with water. Controlled leaks in the liner should be used to test the ability of the TDR system to detect leaks of different sizes, positions, and rates a round the transmission lines. We also need to determine the high frequency electrical properties of some leachate saturated soils. The answers to these recommendations will help us to design a practical TDR monitoring system for detecting leaks from waste pond liners.

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PILOT SCALE VERIFICATION OF A LINER LEAK DETECTION SYSTEM

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ABSTRACT

Flexible membrane materials have been used as liners at landfills and surface impoundments to inhibit fluids from contaminating surrounding water resources. These materials will act as an electrical insulator in such installations. Therefore, any leak in the liner will form a detectable electric current path by which a leak may be detected and located. The primary objective of this project is to develop a method to detect and locate leak paths in membrane liners.

A summary of the two- and three-dimensional electrical modelling of liners with leaks, using computers and physical scale models is presented. Search techniques developed have led to hardware and planned pilot scale field studies. The system developed for use at landfills and surface impoundments is discussed. Examples of equipotential plots showing leak dependent surface effects are included.

INTRODUCTION

An important aspect of hazardous waste treatment and disposal in landfills or surface impoundments is the prevention of surface and groundwater contamination by fluids containing hazardous constituents. Relatively impervious flexible membrane liners have been used to establish the facility boundaries and to prevent fluids from migrating into the surrounding water resources.

Research and evaluation projects are underway to investigate the effectiveness of waste containment liner materials, including the long-term deterioration of liners exposed to various waste products. Early landfill liners consisted of clay hardpans, and wood or metal barriers. Improved liners have been developed more recently using flexible polymeric materials to provide lower liquid permeability and longer waste containment lifetimes.

While these newer liner materials are demonstrating improved resistance to prolonged waste exposure, no methods are presently available to nondestructively test their physical integrity in service environments. A tear or rupture in a liner system will allow fluid to migrate from the facility and thus violate the original intent of the liner. The work reported herein has been directed towards developing a nondestructive electrical system which can be used for detecting and locating leaks in waste containment liners while the facility remains in service.

Since the philosophy of impervious liners is to contain rather than absorb or filter contaminants, the physical characteristics of the liner materials will usually differ significantly from the underlying soil and the contained hazardous waste. In particular, liners made of impervious plastics and rubbers will exhibit very high electrical resistance which will act as an electrical insulator between the internal and external liner surfaces. If the liner is physically punctured or separated so that fluid passes through the liner, the electrical conductivity of the fluid and saturated underlying soil will form a detectable electric current path through the liner by which the leak may be revealed. Electrical methods are attractive because they can be applied on the surface of the landfill or fluid impoundment. The methods are completely nondestructive in operation and, by means of automated field equipment, can be made very efficient and cost-effective for facility monitoring operations. The resulting method, when fully developed, will be useful for surveying existing as well as new facilities where electrically resistive membrane liners are installed.

Two- and three-dimensional computer models were used to examine the current distribution in the cross sections of several simulated liner geometries having different leak locations. In addition to these analytical model studies, a three-dimensional physical scale model was also constructed using a plastic liner in a wooden frame. Soil was placed inside the model to simulate a landfill. Water was used to simulate a fluid impoundment. Electrical potential distributions on the surface of the soil and water were measured to determine the effects of punctures in the liner. The effects of multiple leaks as well as those caused by subsurface anomalies contained within the liner were studied. Based upon these application concept studies, the most promising electrical testing methods were identified and subsequent project activities were directed towards the design and fabrication of an appropriate experimental field instrumentation system. Computer software has also been developed and tested to allow on-site analysis of field data.

EXPERIMENTAL METHOD

Figure 1 shows the basic electrical testing concept where one current electrode is located away from the facility and a current path exists through a leak penetration in the liner as well as over the buried edge of the liner. This figure illustrates that when a leak penetration is present in the liner, current flow between electrodes located inside and outside the facility will follow two paths, namely, through the leak and over the buried edges of the liner. Since surface potentials are directly related to the current distributions in the vicinity of the search electrode, they can be used to locate the leak.

The first numerical model study used a general purpose circuit simulation computer program (SPICE). Circuits containing resistors, capacitors, inductors, and voltage and current sources were simulated with the program. A two-dimensional resistor network model designed to simulate a membrane liner was modelled using the program.

Figure 2 illustrates a contour plot showing the two-dimensional potential distribution around a liner without leaks. The current injection point is at the top of the figure with the other reference electrode connected to a conducting path along the bottom and sides of the cross section. The outline of the liner has been sketched in the figure and is represented by the three-sided trapezoidal figure in the center of the plots. The equipotential lines showing the voltage distribution patterns were computer generated. The current flow paths are at right angles to the equipotential lines and were sketched in by hand. Figure 2 illustrates the current flow over the edges of the liner and into the surrounding earth.

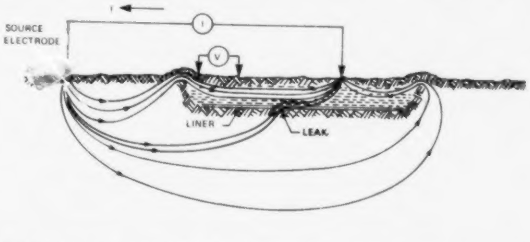

FIGURE 1. LEAKING LINER. ARBITRARY SEARCH ELECTRODE POSITION

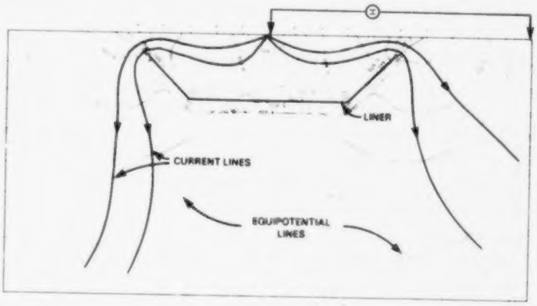

FIGURE 2. COMPUTER-MODELED VERTICAL CROSS-SECTION OF WASTE LINER WITH NO LEAKS

In parallel with the computer analysis work described above, a three-dimensional physical scale model was constructed in an outdoor environment where ground is used as the soil underlying the physical scale model. Figure 3 shows the model and the instrumentation van.

Surface voltages were measured with potential measurement electrodes located in the basin. The potential reference electrode was fixed in position near one corner of the model. The exploration measurement electrode was composed of many electrodes mounted on a fiberglass beam at 6.35cm (2.5 in.) spacings. Most of the data were acquired using a polar grid with the current injection electrode at the center.

The leaks in the bottom of the liner were generated by driving a 1.524cm (0.5 in.) diameter copper-clad steel rod through the liner and into the soil. This rod provided a good conducting path between the water and the soil without loss of water.

EXPERIMENTAL RESULTS

Figure 4 illustrates the results of one of the computer generated two-dimensional analyses of a liner having a leak in the bottom. The equipotential lines which appear in the figure were generated and plotted automatically by the computer program described earlier.

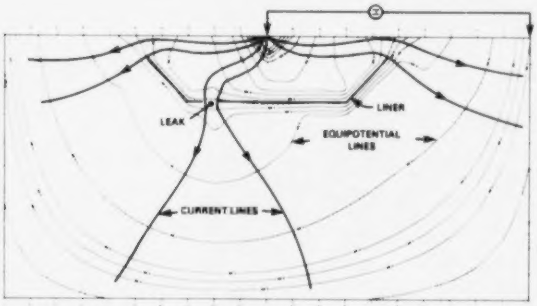

FIGURE 4. COMPUTER MODELLED VERTICAL CROSS-SECTION OF A WASTE LINER WITH A LEAK IN THE BOTTOM

This result shows that, as predicted, when a leak penetration is present in the liner, current flow between electrodes located inside the outside the liner will follow two paths, namely, through the leak and around the buried edges of the liner. Note the non-symmetry of the equipotential lines terminating on the surface of the landfill above the liner. The voltage gradient is clearly steeper along the surface on the side of the current injection electrode above the leak. Asymmetries such as were investigated in subsequent work to develop field measurements which could locate liner leaks.

Figures 5 and 6 show examples of equipotential contours measured using the physical scale model. For all plots, the current injection point is located at the center of the polar coordinate system. In Figure 5, a single leak was located at an arbitrary position in the bottom. Figure 6 clearly shows the ability of the technique to distinguish between multiple leaks.

Many data acquisition runs were conducted using different combinations of water and soil depth, distance between current inejction point, leak position, number of leaks, and conductive anomalies in the water. All of the tests resulted in similar types of equipotential plots in which the leak position could be accurately inferred.

To verify the system performance prior to conducting a survey in the field, a full scale verification program is being implemented. A one-acre lined test facility has been constructed on the SwRI grounds. A two-phased effort is planned for testing the system using this facility. Phase One will involve testing the system with water in the test facility. Phase Two tests will use an earth fill over the liner. The intent of each phase is to gather additional data to predict the usefulness of the survey system at lined fluid storage impoundments and landfills. Details of both the verification phases are presented below.

PHASE I - WATER FILL VERIFICATION

Figure 7 shows the pattern of leaks which are being used in the bottom of the impoundment. The leaks have been induced in the liner by a short length of 12-inch diameter pipe penetrating the liner. An open pipe establishes a leak through the liner; a closed pipe re-establishes the integrity of the liner at the location. For the proposed tests outlined below, no more than two leaks will be opened at a time.

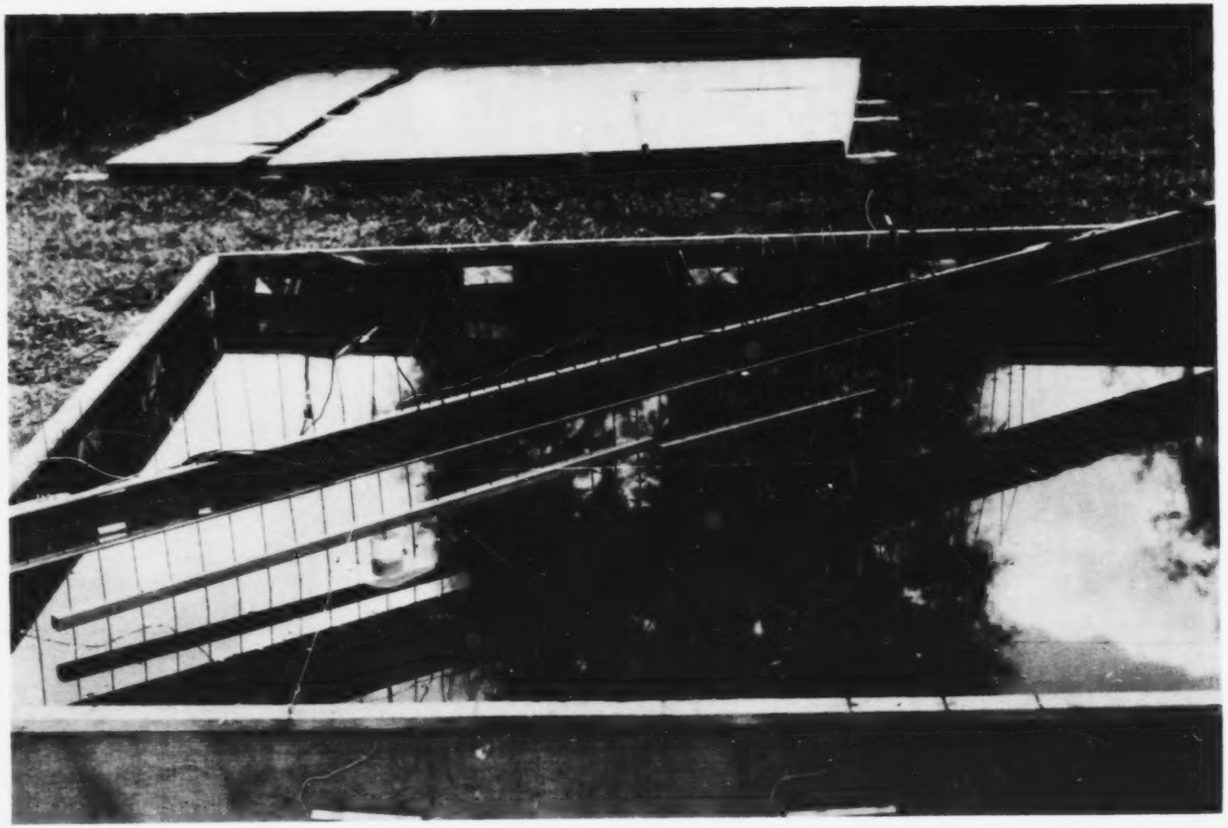

FIGURE 3. THE PHYSICAL SCALE MODEL WITH MEASUREMENT ELECTRODES IN PLACE.

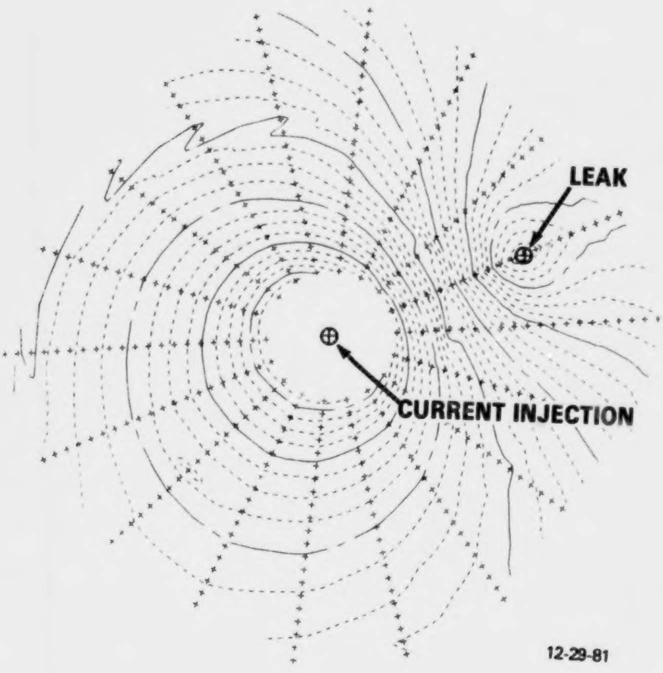

FIGURE 5. EQUIPOTENTIAL PLOT OF VOLTAGES ON THE SURFACE OF AN EARTH FILLED LINER WITH A SINGLE LEAK

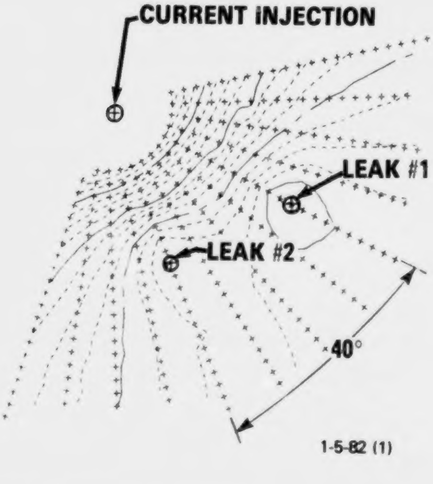

FIGURE 6. EQUIPOTENTIAL PLOT OF VOLTAGES ON THE SURFACE OF AN EARTH FILLED LINER WITH TWO LEAKS

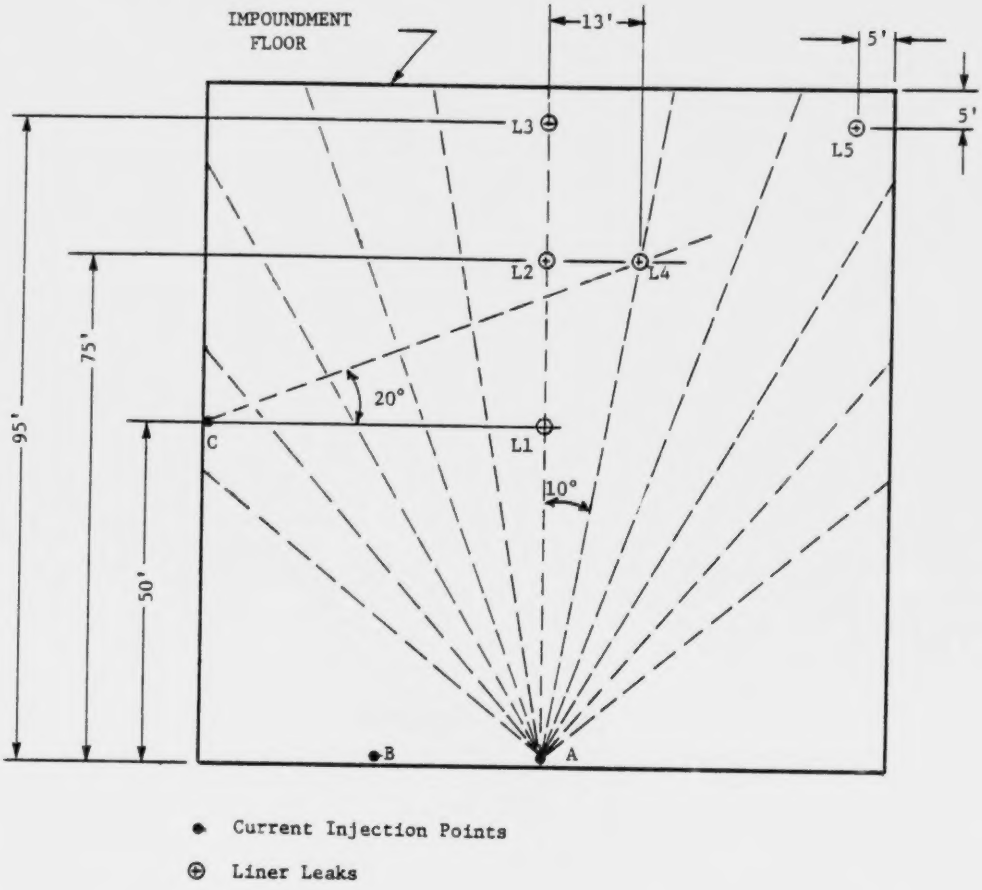
IMPOUNDMENT FLOOR
13'
5'
5'
L3
L5
L2
L4
75'
95'
20°
C
L1
10°
50'
B
A
● Current Injection Points
⊕ Liner Leaks

FIGURE 7. CURRENT INJECTION AND LEAK POINTS FOR THE ELECTRICAL RESISTIVITY SURVEY

The leaks to be studied are labeled in the figure as L1, L2, L3, L4, and L5. Leak L1 is selected to be in the center of the model and leak L2 is half way between the center and the edge. L3 and L5 were chosen to study the effects of leaks near the edge of an impoundment. Leak L4 was chosen primarily to be paired with leak L2. When viewed from position "A", Leaks L2 and L4 are separated by an angular distance of ten degrees. Linearly they are 13 feet apart.

Current injection points near the edge of the impoundment floor are labeled "A", "B" and "C". Each current injection point will be used to study the effects of all leak points taken one at a time. Leak point L2, L4, and L1, L4 will be studied as pairs, simulating two leaks in close proximity to each other.

The surface potentials will be measured using a single electrode on a winch mounted cable. A winch mounted odometer is used to monitor the distance to the measurement electrode cable. As the measurement electrode is pulled across the surface of the impoundment, the computer used in the data acquisition system will trigger potential measurement based on the preprogrammed recording increment and the odometer readings. The data will be acquired on a polar grid with ten degree increments between radials. For data acquisition and for plotting the results, the current injection electrode is the center of the polar grid.

Polar data for all of the leak combinations listed above will be taken at current injection points. All measurements will be recorded at water depths of one, three and five feet. Thus for the seven leak orientations, the three current injection points and the three water depths, a total of 63 data acquisition runs will be made.

Software written for the HP9825 field desktop computer will provide real time data processing, digital recording and graphic display for the field data. To provide hard copy graphics information, a HP7245 thermal plotter/printer will be used with the computer. The computer interfaces to the odometer and signal conditioning circuits through a multiprogrammer. Contained in the multiprogrammer are circuit modules to interface with the odometer electronics and a 12 bit A/D converter for digitizing the potential measurements.

PHASE 2 - SOIL FILL VERIFICATION

For this phase, the impoundment will be drained and filled with two feet of soil. Leak paths L1, L2, and L4 which were used in the water study will also be used with the soil fill. As with the water study, the leaks will be induced in the liner by a short length of PVC pipe penetrating the liner. To insure electrical continuity through the pipe, a solid core of moist earth will be maintained in the pipe.

In the soil fill study, leak points L1 and L2 will be studied as single leaks. L2 together with L4 will be used to study a liner with two leaks in close proximity to each other. Current injection points "A", "B", "C" will again be used as the center of the polar data acquisition array.

A cable system better suited to working on land will be used to collect data in the soil fill study. To measure soil potentials, a cable system with 24 electrodes and preamps will be spread out in an equally spaced linear array across the surface. Circuits in the data acquisition system will address the preamps one at a time to read and record all potentials. After recording data from one position of the cable, all cables and electrodes are moved to the next position on the same type of polar grid used to record the data over water. Ten degree increments will be used between radials.

Polar data for all leak combinations listed above will be taken at current injection points "A", "B", and "C". Only one soil depth of two feet will be used however. The number of leak combinations and current injection points will result in nine complete data cquisition runs.

The software for the cable data acquisition system will be slightly different than that used with the single electrode winch system. After acquiring the data and recording it, however the real time data processing and display is identical to that used for the water impoundment study.

FIELD TESTING OF THE SYSTEM

After successful completion of these tests, Southwest Research Institute plans to locate at least two actual field sites for additional testing.

The field tests conducted at landfill and surface impoundment facilities will likely duplicate the test procedures outlined above. Slight modifications may be required, depending upon site conditions. The same cable systems, hardware and software will be used that has been developed and tested in the field scale model.

In selecting test sites, technical factors for consideration are the size including depth and surface area, the type of liner material and current waste management procedures such as sump removal of accumulated leachate. Since the method depends upon a conductive path through the liner, removal of leachate could remove the desired electrical shunt. A minimum of one landfill and one fluid impoundment will be selected.

Other parameters to be considered are the age of the site, type of waste material deposited in the landfill, the resistivity nonuniformity of the fill volume, and the type of fluid stored in the case of an impoundment.

Information on known or suspected liner leaks will be helpful in verifying the survey results since purposely introduced liner penetrations will probably not be practical or permissible.

As with the scale field model, data will be acquired on a polar grid pattern. In the full scale field testing, the angular spacing between radials and the linear spacing between potential measurements will be determined by data from the test facility and the depth of the landfill or surface impoundment selected for survey.

Realtime data processing and display will help dictate the direction and pattern of the search over the landfill or surface impoundment. A typical survey will enable the field crew to quickly cover the complete waste liner surface to rapidly identify and tag zones with possible leaks. When such a zone is found, the survey resolution will be increased to provide the maximum delineation of the susepcted leak location.

The desktop computer, portable generator current source, signal conditioning electronics and all other supporting equipment will be transported to the test site in a Department of Geosciences Mobile laboratory.

CONCLUSIONS

Project results to date have demonstrated the ability of the electrical survey system to accomplish the goal of leak detection and location on a small scale. The planned system testing program utilizing the full scale lined facility will further define performance capabilities and establish the confidence level of survey results. These results will be evaluated to form the basis for a decision to test the system at two field sites.

ACKNOWLEDGEMENTS

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DEVELOPMENT OF LINER RETROFIT CONCEPTS FOR SURFACE IMPOUNDMENTS

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INTRODUCTION

Surface impoundment facilities such as pits, ponds, and lagoons are used extensively throughout the United States to store, treat and dispose of hazardous wastes. These impoundments usually are designed to contain fluids, utilizing native materials or liners and in the past, many were constructed with little concern for the prevention of seepage from the facility. In fact, many such facilities were specifically designed to seep water into the ground as a means of disposal. Unfortunately, many of these facilities are presently causing groundwater contamination problems.

With the establishment of regulations passed under authority of the Resource Conservation and Recovery Act (RCRA) legislation, retrofitting in-service disposal and treatment impoundments may be required to prevent continued seepage. Retrofitting with impermeable liners may accomplish this objective. Liners may also be required to protect against wind and water erosion, another objective of RCRA regulation requirements.

Retrofitting an in-service impoundment with a flexible membrane liner generally implies the emplacement of liner material on the bottom and sides of a facility to mitigate leakage without removing any in situ fluid (hazardous material) in the impoundment. Such action may be desirable as a temporary measure while a new impoundment is being constructed; or as a permanent step to upgrade an untrustworthy facility. As RCRA regulations are implemented and groundwater studies confirm contamination from seeping impoundments, information about retrofitting techniques will be needed to assist owners and operators in upgrading existing facilities.

The main purpose of a membrane liner system in a fluid impoundment is to prevent loss of liquid to groundwater resources, but a liner can also prevent bank erosion due to wave and wind action. Flexible liner membranes are manufactured using a variety of polymeric materials such as polyethylene and polyvinyl chloride. In the construction of new impoundments, the sheets of liner membrane materials are installed over compacted subgrade and connected together using a variety of seaming methods. The most common methods are heat sealing and solvent bonding. The sheet is attached at the top of the impoundment perimeter using an anchoring system, usually an earthen anchor trench. The finished liner serves as a relatively impermeable continuous barrier covering the earthen impoundment.

The implementation and enforcement of RCRA regulations concerning hazardous waste impoundment will create a need for owners/operators to cease the contamination of groundwater resources due to seepage. In many cases it may be desirable or even necessary to make design modifications while the facility is in service, while in others it may be necessary to temporarily reduce seepage while a facility is closed or a new one is constructed. Retrofitting of membrane liner systems offers a potential way for owners of such hazardous waste fluid impoundments to reduce or stop seepage.

Unfortunately, retrofitting existing impoundments has not been routinely performed. Many questions need to be answered before this approach to sealing an existing impoundment can be implemented. Information concerning the size of facilities which can be retrofitted, equipment needed, the most efficient retrofitting system, labor requirements and costs needs to be developed.

This paper reports on an ongoing project that Southwest Research Institute is conducting for the U.S. Environmental Protection Agency for the development and demonstration of systems to retrofit existing liquid surface impoundment facilities with synthetic membrane. The project objectives will be stated, the work accomplished described, and future work outlined.

PROJECT OBJECTIVES

The primary objective of this project is to determine the feasibility of retrofitting an existing surface impoundment with an effective membrane liner system without taking the facility out of service. Anticipated project results are the following:

* Identification of one or more technically feasible retrofit liner installation techniques.

* Demonstration of the feasibility of each system on a pilot scale.

* Preparation of a full scale demonstration plan if the systems prove feasible at pilot scale.

The results of the project will determine the feasibility of retrofitting existing surface impoundments with a membrane liner system. Conceptual approaches to retrofitting different types of impoundments will be developed and evaluated. The most promising approaches will be attempted at a pilot scale to verify or deny their feasibility. From these activities, the important procedural and physical parameters to consider when retrofitting will be established. Limitations of each approach will be defined, e.g. which approach is best suited for a particular impoundment geometry. A plan will be developed for full scale implementation of those retrofitting systems shown to be feasible at pilot scale. Potential sites will be identified where the retrofit approaches could be implemented.

The most significant benefit which can be expected as a result of successful completion of this project will be the development of a promising technique(s) which could be used to halt the release of hazardous fluids into the environment. Preventing or stopping the contamination of surface and/or groundwater may be important to protect drinking water supplies. If a surface impoundment containing hazardous wastes is found to be seeping contaminated fluids, retrofitting the facility with an effective membrane liner system should provide mitigation. This project should provide information needed about retrofitting in order to ascertain the feasibility of full scale utilization.

LOAD ANALYSES

A theoretical stress/strain analysis has been performed for the various retrofit membrane materials. Mechanical properties and coefficient-of-friction and failure data for different types of liner material were obtained and used during the analyses. A load analysis program has been written to calculate the stresses on liner materials resulting from installation using the pull-thru concept for retrofitting. The program is set up to run on a HP9325A desktop computer. Required input data is as follows:

* length of the first sheet to be pulled into the pond;

* the footage of liner covering the end slopes of the pond;

* the footage of liner covering the side slopes of the pond;

* coefficients of friction values for soil and water;

* the tensile strength of the liner material at elongation;

* the thickness and density of the liner; and

* the length and width of the pond.

This program will calculate these stresses for any impoundment geometry and liner material. Table 1 presents calculations for four generic liner materials and three different sizes of impoundments. The pond geometry varies as does the size of the panels to be seamed together as the material is pulled into the water.

These calculations provide a very gross estimate of the forces to be expected. Critical factors yet to be answered are, (1) can the maximum force required to pull the liner be distributed evenly along the edge of the liner; (2) what are the coefficient of friction values for each material and how can they be reduced; and (3) what effect will weighting the draw bar to keep the liner on the bottom have on the stress distribution to the liner. The values shown in Table 1 are likely more accurate for the pull-over retrofit concept than the pull-thru concept. Note that the calculated tensile values for all cases do not exceed the tensile at elongation values of the various materials.

CONSIDERATIONS IN RETROFITTING LINERS

A study has been made of considerations in retrofitting liners. Two general approaches to retrofitting ponds have been analyzed. These are pulling the liner along the contour of the pond and pulling the liner on top of the fluid, with subsequent sinking of the liner to conform to the contour. Each approach has positive and negative features. The following discussion presents methods for deployment, advantages and problems and possible mitigating actions. Common features and problems are identified.

PULL-THRU CONCEPT

Method of Deployment

* Assembly - The liner will be assembled by one of three methods:

(1) All of the membrane panels are laid out, seamed and then fan folded.

(2) The panels are laid out, seamed and then fan folded.

(3) The panels are laid out and seamed one at a time.

* Pulling - The leading edge of the assembled panel will be wrapped around a heavy catenary cable or chain or clamped between sections of heavy steel plates to distribute the pulling load along the edge of the panel. A battery of cable pullers or winches would be mounted at the opposite end of the impoundment to pull the panel into and across the basin.

Bottom Contour and Side Slope Following

While new impoundments with membrane liners generally have smooth flat bottoms to facilitate proper placement of the liner, existing unlined impoundments will most likely not have smooth flat bottoms or straight side slopes since that would not have been a design requirement at the time they were built. Thus, even with the use of rollers at the bottom of the side slopes and in the corners, it will be difficult to prevent bridging by the liner as it is pulled across depression in the bottom or irregularities along the sides. Large pockets of liquid would then be trapped beneath the liners. The implications of this entrapped liquid are discussed in a later section. However, drag caused by the digging in of the leading edge of the liner, or by the build up of mud or sludge balls along this edge, can greatly increase the required pulling force or cause the cable or load distributing panel to fail.

Mitigating actions to reduce bridging and entrapment of liquids will be by the frequent use of rollers to keep the liner on the bottom of depressions or irregularities and by the careful design of the leading edge of the load distributing panel to prevent digging in. A slight rise in the weighted leading edge will cause the liner to dig through the sludge but not into the harder underlying soil. If the impoundment is filled with filamentous sludges (as might be the case for some sewage wastes) it may not be possible to place the liner by dragging because of balling of the sludge.

Tearing

Existing impoundments are likely to have protrusions that will cause excessive stress concentrations in the liner and faillure by tearing. Irregularities in the bottom, rocks, pipes and other debris, known or more likely unknown and unseen, can cause ripping. Because the ripping is likely to occur beneath the surface of what is perhaps a murkey liquid the tear may not be noticed or detectable.

Mitigating actions may be to search the impoundment with a drag wire survey to locate and/or remove the larger protrusions, by reducing friction forces so that the localized tension forces at the protrusion are less, and thus the near bouyant liner might ride over it without tearing, or by using a tougher fiber reinforced liner that is less likely to tear on small protrusions.

FLOAT AND SINK CONCEPT (PUMP-OVER)

Method of Deployment

* Assembly - The liner is assembled using one of the methods described for dragging, however, the end that is pulled across the impoundment is doubled back over a stiff hose, or sections of rods, for a sufficient distance so that when the liner is deployed, the end will fall several feet short of the "shoreline" when fully deployed. Clamps around the liner and hose or rods are then installed to permit pulling the liner without excessive strain.

* Placement - The liner will be pulled across the impoundment in a fashion similar to the pull thru concept, however, in this method of placement, the loading edge of the liner and the pulling lines will be kept as light as possible so that the liner would remain on or near the surface during the deployment period.

* Sinking of Liner - The deployed liner will be lightly held in position during the sinking phase. If the liner has a density greater than the liquid it will slowly sink. As it sinks, the liquid underneath the liner would escape and flow over the top at the open water margin between the folded end of the liner and the far shore line. If the liner is made of bouyant material, e.g., HDPE, ballast such a coarse sand would be used to sink the liner. The ballast would be placed on the liner starting at the initial deployment end. Only a small amount of ballast should be required. Only 2½ pounds per 100 square feet should sink 80 mil HDPE. Similar to the dense liner, the displaced water will move towards the gap at the far end as the liner is slowly covered with ballast. When the liner has completely sunk, the doubled back flap is opened up and pulled towards the far end to close the gap. One end of the gap will be left down until the very end to let any remaining liquid escape. For the pump-over concept, fluid would be pumped onto the liner rather than allowing it to flow over the leading edge.

Advantages

Placement of the panel will cause minimal stress to the liner since only the dry land friction should be of any magnitude and, as discussed earlier, this can be mitigated. There should be negligible tearing since the liner is not dragged across potential tearing protrusions. Holing of the liner should be limited to localized punctures by very sharp protrusion. Since the liner sinks under minimum tension, it should settle into most bottom depressions and side irregularities.

SPECIFIC PROBLEMS AND MITIGATING ACTIONS

Sinking and Liquid Recirculation

Even with the provision of a folded back flap at one end to permit the liquid beneath the liner to recirculate to the top, proper sinking of the liner may be difficult to achieve. The liner will probably not sink uniformly by itself but will have to be constrained around the perimeter as it sinks. Otherwise, the liquid underneath may attempt to recirculate to the surface at locations other than planned with the liner settling to the bottom possibly out of position. This could result in excessive folds in the liner or lack of sufficient coverage around the side slopes. Also since the tension in the linear during placement will be less than for dragging, extra care will have to be taken to reduce damage or misplacement due to wind or wave action. Pumping of fluid would allow placement of the water at the end of the facility opposite from the leading edge. This may facilitate controlled sinking of the liner.

Entrapped Liquids and Sludges

Whether by pulling or sinking, some liquid or sludge will be trapped between the liner and the bottom of the impoundment. The specifics of the type of waste and the underlying soil conditions will determine what actions should be taken to accommodate these entrapments.

Non-Gas Generating Entrapments

If the entrapped liquid or the underlying soil does not generate gases, it may be acceptable to leave the liquid and not attempt to remove it. If the underlying soil is permeable enough, and the water table low enough, the entrapped liquid will percolate away. If the underlying soil or entrapped sludge is not permeable, the bubble of liquid will remain. There is then the danger of ripping or perforation of the liner due to the repeated working of the fabric over the bubble under wave induced or other hydraulic motions.

Methods to remove entrapped bubbles of liquid may include the following:

* One-way valves could be widely distributed over the liner. In the placement mode they will assist in the rapid and uniform sinking of the liner and would permit the entrapped liquids to escape. Detrimental aspects of their use will include clogging by the sludge, complexity of installation and susceptibility to damage, and the likelihood of leakage, albeit a small amount due to grit lodging on the valve faces.

* The impoundment could be lined with an array of drain pipes with the inlets covered with porous sand, gravel and/or a geotechnical filter membrane. Entrapped liquids would then be pumped out. The placement of the array in an existing impoundment may be difficult and complex. There will also be susceptibility to drain blockage by sludge.

* By the use of either ballast or weighted rollers, entrapped liquids could be rolled out. Starting in the middle or deepest point of impoundment, ballast is placed on the liner to establish an outward moving radial front of the displaced entrapped liquid. The entrapped liquid is then allowed to escape to the surface around the perimeter. Rollers operating in a sequence of outward moving radial rolls can similarly work the entrapped liquids towards the edges and then the surface.

Gas Generating Entrapments

Many waste liquids, sludges and underlying soils may generate gases. Bubbles of gas under the liner can raise the liner to the surface or at least separate it from the bottom and make it susceptible to wear and failure from hydraulic motions or induced stresses. In some cases, if the waste material and underlying soil are permeable enough, the entrapped gas will escape by itself. However, if the gas cannot escape, then mitigating actions will have to be taken using the methods for removing entrapped liquids or other techniques:

* If clogging of the valves can be prevented and if leakage is acceptable, one way valves can be effective in the removal of entrapped gas. The escaping gas may also unclog the valve.

* Similarly, if clogging can be prevented, drain fields can be used to remove gases.

* Rolling out or ballasting will not be an acceptable method for gas removal unless only a very small quantity of gas is generated for a short period after the retrofit of the liner.

* Non-clogging geotechnical filter membranes that can block sludge or sediment while passing liquids and gases can be installed under the retrofitted liner. They will then conduct the entrapped liquids and gases to the surface or to either one way valves or a drainage field where the gas can escape. Uncertainties with using permeable membranes include the long term blocking of the pores of the material and compression of the pores due to the overlying load of the waste material.

Sludge and Contaminated Soil Removal

The float and sink method will trap all, and the dragging method much, of the solids in the sludge under the retrofitted liner. This sludge and any contaminated soil under the impoundment can leak undesirable trapped liquids or generate gas for many years. In some cases, the leachate may be able to be pumped out from peripheral wells. However, if this practice is determined to be unacceptable it may be necessary to completely remove the sludge and contaminated soil. The size of many impoundments and other constraints will preclude draining the impoundment and temporarily storing the waste material in another impoundment. Thus, the solid material will have to be removed in situ and prevented from settling before the retrofitted liner can be placed. Two methods of dredging and liner installation might be used to achieve this objective. Both methods require that the waste material in the impoundment has the property that suspended solids will settle out under gravitational forces so that there is a clear liquid overlying a sludge blanket. Except for some colloidal suspensions, most aqueous wastes have these properties. Oily wastes may have oil or foam on the surface but there is usually a clear liquid underneath.

* Dragging - As the liner is pulled along the bottom and into position, a dredge will remove the sludge and contaminated soil immediately ahead of the liner. The dredged spoil is initially pumped and discharged at a far corner of the impoundment. There the suspended sediment settles to the bottom and the clear liquid recirculates back into the impoundment. It may be necessary to install a floating silt curtain around the discharge to confine the dredged material until it has settled out. When approximately half the liner is dragged into position, the discharge will be moved so that the spoil is deposited at a far corner of the lined part of the impoundment. Care will have to be taken to widely spread the spoil over the liner since it will still be moving into position and thus, it will be desirable not to create abnormal stresses in the liner by weighting it down with sediment. If there is a very large mass of heavy settled sludge, this method of installation may not be feasible.

* Placement - In this method, part of the impoundment is sectioned off by a floating curtain similar to those used in controlling oil spills. The bottom edge of the curtain is weighted and lies on the bottom of the impoundment as a seal. The sediment from the sections is dredged and deposited far behind the curtain. The clear supernatent is permitted to recirculate over the top of the curtain. After dredging, the liner is placed using the methods discussed earlier. The curtain is then moved to enclose the next adjacent section. After completion of dredging of this section, the liner is placed with an overlap over the previously placed liner. With sufficient overlap, acceptable small leakage rates can be achieved. Similarly to the procedure for the pull-thru method of installation, when the impoundment is half lined the spoil discharge point is moved to a remote position over the retrofitted liner. Since in the placement method of installation the liner is not moved over the bottom, the mass of the settled sediment at a particular place is not as critical using this method. While small road transportable cutter head or dust pan dredges can be used to move the sludge, consideration should be given to pneumatic dredges that have been developed for dredging contaminated sediments. This type of dredge entrains considrably less liquid and the discharged spoil tends to settle out with a considerably smaller surface plume.

* Folds - As was discussed earlier, the topography of impoundments in which retrofitted liners will be placed will most likely be quite irregular. In installing the liner, it will be very difficult, if not impossible, to prevent folding of the liner. Where the liner is above the liquid, as around the sides of the impoundments, folds can be cut out and the liner patched. However, when folds occur in the liner beneath the surface of the liquid waste it may not be possible to remove the folds using these methods. One, the fold may not be detectable if covered by sludge or murky waste. Two, it may not be possible to patch the liner underwater. If the fold is left unattended, the liquid confined in the fold may drain out by itself or may be withdrawn using the methods for removing liquids and gases discussed earlier. However, the base of the fold may seal the fold thus trapping the liquid in the fold. Similar to the entrapped bubble, the material in the fold will work under various hydraulic actions which may ultimately cause the liner to wear or rip. If the fold

matrial just wears enough so the entrapped liquid can escape, the fold may collapse and the two overlapping halves may form a seal. If the fold material tears, the two halves of the fold may move apart and an appreciable leak path may be created. Thus, a liner material that wears and leaks may be preferable to one that doesn't wear but tears. Folds in the subsurface part of the retrofitted liner may have to be accepted. Perhaps in areas where folds are likely to be encountered, a second layer will be installed to reduce leakage through failed folds.

DOUBLE PERFORATED LINER WITH PERMEABLE GEOTECHNICAL FILTER MEMBRANE

For the many reasons discussed in this presentation, the probability of having leakage after the installation of a retrofitted liner is quite high. Proper design, selection of materials and placement can result in an installation with greatly reduced leakage but there is still likely to be some. If this less than perfect performance is acceptable then the utilization of two layers of liners that are intentionally perforated may lead to a superior installation system. Aspects of a two liner system are:

* Installation - If the perforated liner is installed using the placement method it will sink more rapidly than a non-perforated liner and will require less control around the perimeter. Any residual trapped liquid will be displaced as the liner sinks to the bottom. Liquid trapped in folds will also readily leak out, permitting the fold to collapse. in the installation of buoyant liners, porous ballast such as sand or gravel would not block the perforations. If the second layer of the perforated liner is laid at right angles to the first, likelihood of folds lying on top of each other and of being parallel is reduced.

* Perforations - Perforations in the liner would not be uniformally placed but would be located in a pseudo-random pattern. That is, there might be one hole randomly placed in each square foot. With this random placement there would not be a row of holes in one liner aligning over a row of holes in the other liner.

* Leakage - If the lower layer is lying firmly on the bottom and the facing surfaces of the two liners are clean than the double perforations would make an effective one-way valve or hydraulic diode. Either due to negative buoyance or added ballast the two layers will be pressed together blocking any leakage. If there is any trapped liquid or gas at a higher pressure than the overlying liquid, the upper layer will lift, permitting the gas or liquid to escape through the perforations in the upper layer. Once the fluid has escaped, the pressure is reduced and the upper layer will collapse resealing the bottom layer. Since, with many randomly placed holes, some holes in one layer will align up with holes in the other layer there will be some leakage. However, the area of the perforations will be a very small part of the total area so leakage would be very small for a double layer system. A 3/8-inch hole in every square foot of each liner would permit the upward flow of all trapped liquids, yet would have a porosity of less than 10^{-3}. A double layer would then have a porosity of less than 10^{-6}. When combined with existing porosity of the impoundment bottom there should be very little leakage.

* Clogging - the efficiency of a perforated double layer retrofitter liner system is dependent upon keeping the perforations open and the facing surfaces of the liner clean. Blockage of the perforations will not permit the trapped fluids to escape and grit caught between the two layers might create a leakage path. If a liquid and gas permeable geotechnical filter membrane is installed under the perforated liners, sludge and grit underneath would not move up and block the perforations or contaminate the facing surfaces of the liners. A very effective retrofitted liner system would then be achieved.

* Gas - Gas trapped beneath the liner system or subsequently generated in the underlying sludge or soil will be able to escape through the filter membrane to a perforation and then to the surface. If there is a heavy or impermeable waste fill in the impoundment, the gas will move laterally until it can escape through an unblocked perforation or until it reaches the surface around the perimeter of the impoundment.

LABORATORY SCALE STUDIES

A 10 foot by 20 foot scale model impoundment has been constructed and is being used to make qualitative studies or retrofitting liners. The model was constructed outside on the ground, lined with 10 mil black polyethylene sheeting for water retention and then filled with an inch or so of sand to simulate an unlined impoundment. The sand was also banked up the sides and stabilized with cement.

At the time of writing only one series of experiments has been undertaken: the floating and sinking by pump-over of a buoyant membrane liner. A 4 mil polyethylene liner was pulled over and floated on the impoundment, overlapping both the sides and ends. Water was pumped from one end and released at the opposite end at the same time as sand ballast was being put on the liner to sink it. The following observations were then made:

* The liner would not sink to the bottom even with the ballast and water added. Archimedean buoyance forces and tension in the liner from friction forces around the perimeter kept the liner afloat.

* The liner was moved back several inches from the pumping end of the impoundment and a fold worked back towards the ballasted end. When the fold was adjacent to the ballast the liner would then sink to the bottom.

* With no longitudinal tension the ballasted section of the liner will fold under the remaining buoyant liner. Light tension will keep the size of this fold manageable.

* An advantage of floating and sinking is that the liner is not dragged over the bottom. However, the liner will move a little along the sides of the impoundment as it is sunk. Provision will have to be made to accommodate this movement without overstressing the liner.

PILOT SCALE DEMONSTRATION

A pilot scale demonstration facility has been designed and built to test the retrofit system on a larger scale. The facility has been constructed on the ground of Southwest Research Institute. It allows field testing of retrofit concepts under controlled conditions and in the absence of hazardous fluids. This is necessary in the early stages of system development to avoid risk of injury to field crews.

FUTURE WORK

Following further laboratory scale studies retrofitting concepts will be selected for demonstration in the pilot scale facility. The pilot scale demonstration will be conducted and then evaluated. A retrofit system field test plan for an actual hazardous waste site will then be developed.

ACKNOWLEDGEMENT

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LONG TERM IMPACTS OF HAZARDOUS WASTE CODISPOSAL IN LANDFILL SIMULATORS

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ABSTRACT

This project was initiated to simulate landfill decomposition and contaminant release under controlled conditions. The research objectives were to determine effects on solid waste decomposition by the addition of different water infiltration rates, by prewetting the refuse mass, and by codisposing municipal refuse with sewage sludge and various hazardous wastes. To this end, 19 landfill simulators were constructed in late 1974 and early 1975. Each test cell was loaded with approximately 3.0 metric tons of municipal refuse. Selected cells received quantities of hazardous waste additives. Maintenance and operation of these landfill simulators has continued to this date and cells are monitored for temperature, gas quantity and quality, and leachate volume and composition. This paper presents seven years of results for the hazardous waste codisposal cells and describes leachate concentration histories using a semi-empirical leaching model.

INTRODUCTION

As described by the Resource Conservation and Recovery Act (RCRA) regulations promulgated by the U.S. Environmental Protection Agency (EPA) in May 1980, generators of less than 1,000 kg of hazardous waste per month may treat or dispose of their wastes without complying with the full RCRA program. That is, if small quantity generators comply with the regulations for acutely hazardous waste and on-site hazardous waste accumulation, they are then exempt from RCRA requirements. The hazardous waste of these generators is typically sent to municipal landfills which may not be designed for disposal of such wastes. As a result, the possibilities of chronic environmental problems have prompted public scrutiny of hazardous waste codisposal in municipal landfills.

Leachate generation from municipal landfills is the result of moisture from percolating rainfall and surface water, from infiltrating ground water, or from the refuse itself as delivered. Since the chemical composition of the leachate varies depending on the original waste mass, the degree of compaction, the penetration of air and water, and the age of the landfill, research designed to test these variables will yield better methods of prediction for leachate generation and contaminant release.

This research project, motivated by the need to describe landfill decomposition and contaminant release under controlled conditions, addresses the impacts of hazardous waste codisposal in landfill simulators. The overall objectives were to determine the effects on solid waste decomposition by the addition of different water infiltration rates, high initial water content, sewage sludge, calcium carbonate, and six industrial hazardous wastes. The purpose of this paper is to present the data acquired after seven years of project operation and to evaluate long term impacts associated with the disposal of hazardous wastes into municipal landfills.

BACKGROUND

The project was initiated in 1974 to simulate the decomposition of municipal solid waste and to demonstrate effects on that decomposition process by the addition of extra precipitation, pH buffering compounds, sewage sludges, and industrial wastes. A total of 19 landfill simulators were constructed according to the program design in Table 1. Four test cells, containing only municipal refuse to serve as controls, received different water infiltration rates. Three other test cells also served as controls but are located in the laboratory and operated at room temperatures. Low, medium, and high quantities of sewage sludge were added to Test Cells 5, 6, and 7, respectively. Test Cell 8 received calcium carbonate as a pH buffer additive. As shown in Table 1, selected industrial wastes and sludges were added to six test cells and an initial water addition was made to the municipal refuse of Test Cell 11. The operation of Test Cell 15 (polio virus addition) was discontinued in the early stages of the project. The 19 test cells for this program were constructed, loaded, and completely sealed in November 1974 and April 1975.

The project site for this study is the EPA Center Hill Laboratory in Cincinnati, Ohio. Fifteen of the landfill simulators are located outdoors and below the ground surface. As indicated in Figure 1, these fifteen are arranged in a horseshoe alignment with a central leachate collection well. The remaining four test cells are located above ground and inside the high-bay area of the Center Hill Laboratory facility.

METHODS

Initial activities included test cell construction, loading, and waste characterization. On-going operations include water infiltration, leachate drainage, and monitoring of cell gases, leachate, and temperatures. Individual test cells consist of steel tubes 1.83 m in diameter, 3.6 m high, and 4.76 mm thick. Steel sidewalls were coated and sealed with coal-tar epoxy prior to placement. The outside test cells were placed on concrete slabs with layers of fiberglass cloth lining the bottom sidewall (0.3 m) to ensure a water and gas seal. The interior test cells had welded steel bases.

Provisions for leachate drainage were installed in all cells. Leachate drainage for the exterior cells is through connective piping to a central leachate collection well. Interior cells are placed

TABLE 1. PROGRAM DESIGN

Test Cell	Initial Loading Additive	Annual Infiltration	Construction/ Loading Date Nov. 1974	April 1975
1	Control	203 mm	x	
2	Control	406 mm	x	
3	Control	610 mm	x	
4	Control	813 mm	x	
5	Sewage Sludge	406 mm	x	
6	Sewage Sludge	406 mm	x	
7	Sewage Sludge	406 mm	x	
8	Calcium Carbonate	406 mm	x	
9	Petroleum Sludge	406 mm		x
10	Battery Waste	406 mm		x
11	Water	406 mm	x	
12	Electroplating Waste	406 mm	x	
13	Inorganic Pigment Waste	406 mm	x	
14	Chlorine Production Brine Sludge	406 mm	x	
15	Polio Virus	Discontinued	x	
16	Control*	406 mm	x	
17	Solvent-Based Paint Sludge*	406 mm	x	
18	Control*	406 mm		x
19	Control*	406 mm		x

* These test cells located inside the Center Hill Laboratory high bay area. All others located outside and below ground surface.

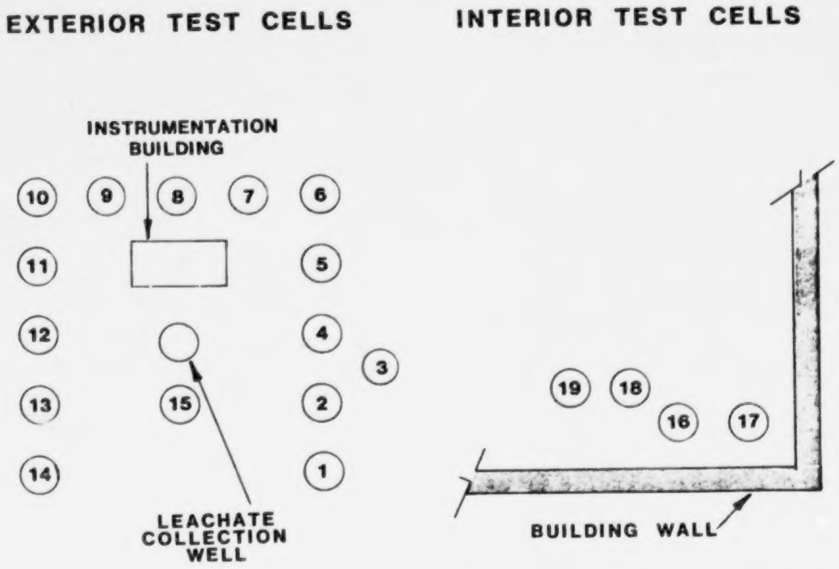
EXTERIOR TEST CELLS
INTERIOR TEST CELLS
INSTRUMENTATION BUILDING
10
9
8
7
6
11
5
12
4
3
13
15
2
14
1
LEACHATE COLLECTION WELL
19
18
16
17
BUILDING WALL

Figure 1. Test Cell Location Plan.

on concrete blocks with leachate drains mounted into the cell bases.

The test cell loading operation began with a 15.2 cm thick layer of silica gravel spread on the bottom of each cell. Refuse was delivered to the site and added to each test cell in eight 0.3 m thick lifts. Each lift was compacted with a wrecking ball. Sludges and other additives were applied at the top of all but the first lift. Temperature probes were installed atop the second, fourth, and sixth lifts in each cell. Gas probes were installed atop the second, sixth, and cover lifts. After loading the waste mass, a layer of silty clay cover soil followed by a layer of pea gravel were added to the test cells. A water distribution line was installed and steel lids were then welded into place. A cross section of a typical test cell is shown in Figure 2.

Test cell loading features have been summarized in Table 2. As indicated, all cells received approximately 3,000 kg of municipal refuse (wet weight). Selected cells received from 68 kg to 2,039 kg of waste additives mixed in proportionate amounts for each lift except the bottom lift. For example, Test Cell 12, loaded with 11.5 percent (dry weight basis) of additive, received 1,190 kg of electroplating waste. Thus, total

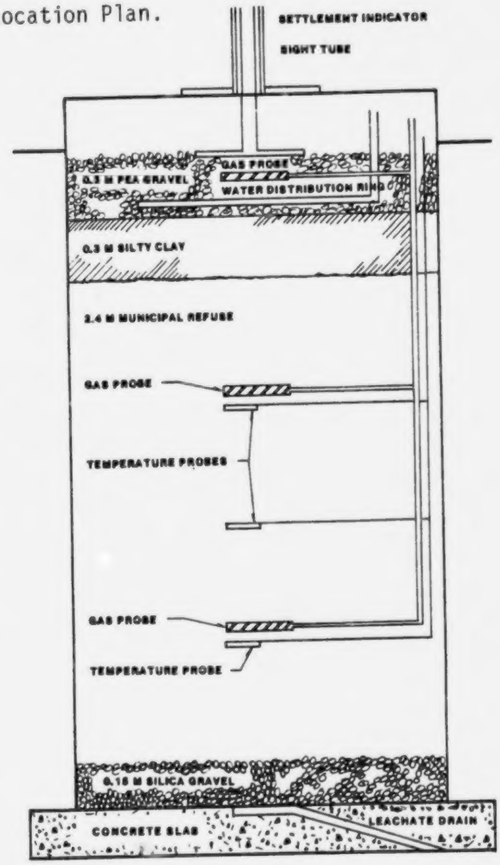
SETTLEMENT INDICATOR
SIGHT TUBE
GAS PROBE
0.3 M PEA GRAVEL
WATER DISTRIBUTION RING
0.3 M SILTY CLAY
2.4 M MUNICIPAL REFUSE
GAS PROBE
TEMPERATURE PROBES
GAS PROBE
TEMPERATURE PROBE
0.15 M SILICA GRAVEL
CONCRETE SLAB
LEACHATE DRAIN

Figure 2. Test Cell Cross Section.

TABLE 2. TEST CELL LOADING FEATURES

	Test Cells																	
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	16	17	18	19
Refuse																		
Solids Content (% of wet weight)	61.8	61.8	61.8	61.8	61.8	61.8	61.8	61.8	69.6	69.6	61.8	61.8	61.8	61.8	61.8	61.8	69.6	69.6
Wet Weight (kg)	3025.0	2989.0	3007.0	3002.0	3001.0	2919.0	2964.0	2994.0	3001.0	2998.0	2924.0	3048.0	3006.0	3015.0	2996.0	2998.0	3000.0	3012.0
Dry Weight (kg)	1869.5	1847.2	1858.3	1855.2	1854.6	1803.9	1831.8	1850.3	2088.7	2086.6	1807.0	1883.7	1857.7	1863.3	1851.5	1852.8	2088.0	2096.4
Mix Ratio (additive as % of total additive/refuse mass - dry weight basis)	--	--	--	--	0.4	1.3	4.3	4.2	13.2	6.2	--	11.5	27.0	45.4	--	39.5	--	--
Additive - Type	--	--	--	--	Sewage Sludge	Sewage Sludge	Sewage Sludge	Calcium Carbonate	Petroleum Sludge	Battery Waste	Water	Electro-plating Waste	Inorganic Pigment Waste	Chlorine Prod.Brine Sludge	--	Solvent Based Paint Sludge	--	--
Solids Content (% of wet weight)	--	--	--	--	12.0	12.0	12.0	90.0	21.0	10.7	0.0	20.5	48.3	75.9	--	75.3	--	--
Wet Weight (kg)	--	--	--	--	68.0	204.0	680.0	90.7	1518.0	1291.0	1293.2	1190.4	1420.6	2038.7	--	1604.0	--	--
Dry Weight (kg)	--	--	--	--	8.2	24.5	81.6	81.6	318.8	138.1	0.0	244.0	686.1	1547.4	--	1207.8	--	--
Total																		
Solids Content (% of wet weight)	61.8	61.8	61.8	61.8	60.7	58.5	52.5	62.6	53.3	51.9	42.8	50.2	57.5	67.5	61.8	66.5	69.6	69.6
Wet Weight (kg)	3025.0	2989.0	3007.0	3002.0	3069.0	3123.0	3644.0	3084.7	4519.0	4289.0	4217.2	4238.4	4426.6	5053.7	2996.0	4602.0	3000.0	3012.0
Dry Weight (kg)	1869.5	1847.2	1858.3	1855.2	1862.8	1828.4	1913.4	1931.9	2407.5	2224.7	1807.0	2127.7	2543.8	3410.7	1851.5	3060.6	2088.0	2096.4
Volume (m^3)	6.4	6.4	6.4	6.4	6 4	6.4	6.4	6.4	6.4	6.4	6.4	6.4	6.4	6.4	6.4	6 4	6.4	6.4
Density																		
Wet weight (kg/m^3)	472.7	467.0	469.8	469.1	479.5	488.0	569.4	482.0	706.1	670.2	658.9	662.3	691.7	789.6	468.1	719.1	468.8	470.6
Dry Weight (kg/m^3)	292.1	288.6	290.4	289.9	291.1	285.7	299.0	301.9	376.2	347.6	282.3	332.5	397.5	532.9	289.3	478.2	326.3	327.6

wet weight for the test cells ranged between 2,989 kg and 5,054 kg. With waste compartment volumes of 6.4 m^3, the final densities achieved for all cells ranged from 467 kg/m^3 and 790 kg/m^3.

To closely simulate in-field landfill conditions, all test cells are operated on a strict monthly schedule of moisture application. This infiltration schedule is presented in Table 3. As shown, Test Cells 1, 3, and 4 receive approximately 200, 600, and 800 mm of annual infiltration, respectively. All remaining test cells receive the 406 mm annual infiltration rate and simulate average precipitation/percolation conditions in the Midwest U.S. The annual rates are administered on a monthly basis, but no infiltration is applied in the usually dry months of January, July, August, and September. High amounts of infiltration are applied in the normally wet months of March, April, and May.

Physical data recording, sampling, and analyses are performed on 18 test cells due to the discontinuance of Test Cell 15. The monitoring program is presented in Table 4 and indicates the extensive analytical efforts conducted on leachate samples. Leachate samples are collected and analyzed for 25 parameters each month; with an additional 8 parameters each quarter, and one parameter every six months. As shown in Table 4, additional parameters were monitored during the course of the project. However, these parameters were not detected at some point since 1974 or were not deemed useful for describing landfill behavior and thus monitoring was discontinued.

RESULTS

Due to the large analytical program for the project, the data cannot be fully evaluated in this presentation. The authors present the following results obtained from two municipal refuse control cells (Nos. 2 and 4) and the six hazardous waste codisposal cells. These six cells contain the following industrial additives: Test Cell 9, petroleum sludge; Test Cell 10, battery waste; Test Cell 12, electroplating waste; Test Cell 13, inorganic pigment sludge; Test Cell 14, chlorine production brine sludge; and Test Cell 17, solvent-based paint sludge.

Refuse and Waste Composition

The refuse was characterized by physical and chemical composition prior to test cell loading. The refuse physical composition was determined by hand surveys for both loading operations (November 1974 and April 1975). Table 5 indicates the results from the sorting procedures based on the 11 refuse categories. Results from the two surveys did not statistically differ ($P<0.05$) with the exception of the garden waste category. Paper was the major component (41.8 percent by weight) of the municipal refuse sample.

TABLE 3. INFILTRATION SCHEDULE

Month	Quantity Per Month (Liters)			
	203 mm Annual Rate*	406 mm Annual Rate+	610 mm Annual Rate#	813 mm Annual Rate**
January	0	0	0	0
February	48.45	96.90	145.72	194.17
March	97.09	194.17	291.45	388.34
April	97.09	194.17	291.45	388.34
May	97.09	194.17	391.45	388.34
June	48.45	96.90	145.72	194.17
July	0	0	0	0
August	0	0	0	0
September	0	0	0	0
October	48.45	96.90	145.72	194.17
November	48.45	96.90	145.72	194.17
December	48.45	96.90	145.72	194.17
Total	533.52	1,067.01	1,702.95	2,135.87

* Test Cell 1.
+ Test Cells 2, and 5-19.
# Test Cell 3.
** Test Cell 4.

TABLE 4. MONITORING PROGRAM

Medium	Parameter	Maximum Frequency
Refuse	Composition	Once, Initially
	Percent Moisture	Once, Initially
	Chemical Oxygen Demand	Once, Initially
	Total Kjeldahl Nitrogen	Once, Initially
	Total Phosphate	Once, Initially
	Inorganic Carbon	Once, Initially
	Organic Carbon	Once, Initially
	Manganese	Once, Initially
	Potassium	Once, Initially
	Magnesium	Once, Initially
	Calcium	Once, Initially
	Sodium	Once, Initially
	Copper	Once, Initially
	Nickel	Once, Initially
	Arsenic	Once, Initially
	Selenium	Once, Initially
	Mercury	Once, Initially
	Lead	Once, Initially
	Beryllium	Once, Initially
	Cadmium	Once, Initially
	Iron	Once, Initially
	Zinc	Once, Initially
	Chromium	Once, Initially
	Lipids	Once, Initially
	Ash	Once, Initially
	Crude Fiber	Once, Initially
	Sugar	Once, Initially
	Starch	Once, Initially
	Asbestos	Once, Initially
Industrial Wastes	Percent Moisture	Once, Initially
	Total Solids	Once, Initially
	Total Volatile Solids	Once, Initially
	Copper	Once, Initially
	Nickel	Once, Initially
	Arsenic	Once, Initially
	Selenium	Once, Initially
	Mercury	Once, Initially
	Lead	Once, Initially
	Beryllium	Once, Initially
	Cadmium	Once, Initially
	Iron	Once, Initially
	Chromium	Once, Initially
	Cyanide	Once, Initially
	Tin	Once, Initially
	Antimony	Once, Initially
	Vanadium	Once, Initially
	Titanium	Once, Initially
	Boron	Once, Initially
	Chloride	Once, Initially
	Asbestos	Once, Initially
Gas	Methane (CH_4)	Monthly
	Carbon Dioxide (CO_2)	Monthly
	Nitrogen (N_2)	Monthly
	Oxygen (O_2)	Monthly
	Hydrogen (H_2)	Monthly*
	Volume	Daily
Test Cell/Air	Temperature	Daily
	Air Pressure	Daily
Leachate	Volume	Monthly
	Temperature	Monthly
	pH	Monthly
	Special Conductivity	Monthly
	Oxidation-Reduction Potential (ORP)	Monthly
	Chemical Oxygen Demand (COD)	Monthly
	Total Organic Carbon (TOC)	Monthly
	Alkalinity	Monthly

TABLE 4. MONITORING PROGRAM (Continued)

Medium	Parameter	Maximum Frequency
Leachate	Hardness	Monthly*
	Total Kjeldahl Nitrogen (TKN)	Monthly
	Total Solids (TS)	Monthly
	Dissolved Solids	Monthly*
	Total Volatile Solids (TVS)	Monthly
	Sulfur (S)	Monthly*
	Chloride (Cl)	Monthly
	Boron (B)	Monthly*
	Cyanide (CN)	Monthly*
	Asbestos	Monthly*
	Phenol	Monthly
	Iron (Fe)	Monthly
	Copper (Cu)	Monthly
	Calcium (Ca)	Monthly*
	Magnesium (Mg)	Monthly*
	Sodium (Na)	Monthly*
	Potassium (K)	Monthly*
	Zinc (Zn)	Monthly
	Cadmium (Cd)	Monthly
	Manganese (Mn)	Monthly*
	Mercury (Hg)	Monthly
	Scandium (Se)	Monthly*
	Beryllium (Be)	Monthly
	Arsenic (As)	Monthly
	Vanadium (V)	Monthly
	Nickel (Ni)	Monthly
	Ortho-Phosphate (O-PO_4)	Monthly
	Sulfide ($S^=$)	Monthly
	Selenium (Se)	Monthly
	Total Phosphorus (PO_4)	Quarterly
	Volatile Acids	Quarterly
	Total Chromium (Cr)	Quarterly
	Lead (Pb)	Quarterly
	Tin (Sn)	Quarterly
	Total Coliform	Quarterly
	Fecal Coliform	Quarterly
	Fecal Streptococci	Quarterly
	Titanium (Ti)	Semi-Annually*
	Antimony (Sb)	Semi-Annually*
	Oil and Grease	Semi-Annually*
	Aluminum (Al)	Semi-Annually*
	Silver (Ag)	Semi-Annually

*Analysis discontinued during monitoring period.

TABLE 5. REFUSE PHYSICAL COMPOSITION

	Wet Weight (%)			
Component	November 1974	April 1975	Composite Mean+	Standard Deviation
Paper	41.0	43.8	41.8	4.6
Garden Waste	16.0	10.9	16.6	6.0
Metal	8.3	7.9	8.4	1.4
Food Waste	7.7	9.1	7.9	1.9
Glass	8.0	7.8	7.8	1.5
Plastic, Rubber, Leather	6.5	8.0	6.9	1.8
Textiles	3.9	3.1	4.1	1.6
Fines*	3.3	2.7	3.1	0.7
Ash, Rock, Dirt	2.4	2.8	2.9	1.3
Diapers	1.9	1.6	2.4	1.0
Wood	1.0	2.0	1.7	1.0

* Material passing through a 25-mm (1.0 in.) sieve.
+ Values are composites of eight lifts from each of 19 test cells.

The industrial hazardous wastes were characterized for chemical composition to determine the loading inputs of various parameters. Results for these parameters are presented in Table 6 and significantly high concentrations are noted in selected cells for copper, arsenic, selenium, mercury, lead, iron, chromium, cyanide, tin, and asbestos. Sub-samples of the industrial wastes were also obtained for moisture content determinations. As shown in Table 5 and derived for Table 2, the industrial wastes ranged from 24 to 89 percent moisture. In particular, the chlorine production brine sludge and the solvent-based paint sludge were very thick additives with total solids contents of approximately 75 percent at the time of loading.

Leachate Volume

Leachate samples are withdrawn once a month prior to water addition. The volume of leachate is used in conjunction with the water added volume to determine the moisture balance and field capacity of each cell.

Municipal refuse is able to retain a certain quantity of moisture in addition to the initial moisture content. This retention quantity can be determined when the initial refuse moisture plus the moisture added causes a flow of leachate. Figure 3, which illustrates the moisture balance for Test Cell 2, determines the moisture retained by the difference of the two plots. The moisture retained, also termed the field capacity, is the maximum moisture content which the solid waste can retain in a gravitational field without producing continuous downward percolation. A simplified equation used to define the moisture balance in refuse mass at any time is:

Moisture Retained = (initial moisture) + (moisture added) - (moisture leached)

One component of this moisture balance equation is the quantity for moisture leached or leachate volume. Figure 4 depicts the cumulative leachate volumes measured for the test cells with different infiltration rates. The plots illustrate that increasing infiltration rates yield greater cumulative leachate volumes. Approximately 15,000 liters of leachate or moisture have passed through the refuse mass in Test Cell 4 in about 2,600 days.

Table 7 summarizes moisture balances for selected test cells at the time of

TABLE 6. WASTE CHEMICAL COMPOSITION

	Industrial Waste (Test Cell)					
Parameter (Units)	Petroleum Sludge (9)	Battery Waste (10)	Electro-plating Waste (12)	Inorganic Pigment Waste (13)	Chlorine Production Brine Sludge (14)	Solvent-Based Paint Sludge (17)
Copper (ppm)	3,500	1,125	100	110	125	2.0
Nickel (ppm)	23	32	35	10	65	0.5
Arsenic (ppm)	1.0	72	460	3.4	14.5	12.8
Selenium (ppm)	26.0	180	4.50	16.0	16.5	7.60
Mercury (ppm)	10.6	4.80	14.7	7.60	227	16.7
Lead (ppm)	182	3.48*	267	120	697	12.6
Beryllium (ppm)	4.8	1.8	0.25	20.2	ND	ND
Cadmium (ppm)	0.50	29.0	38.5	10.5	0.70	0.50
Iron (ppm)	5,560	2,950	1.37*	1,000	2,000	150
Chromium (ppm)	125	155	1.56*	0.50	5.00	75.0
Cyanide (ppm)	1.0	4.2	460	3.4	14.5	12.8
Tin (ppm)	NA	6,800	NA	NA	NA	NA
Antimony (ppm)	NA	1.32*	NA	NA	NA	NA
Vanadium (ppm)	NA	120	NA	40	NA	NA
Titanium (ppm)	NA	NA	NA	NA	ND	NA
Boron (ppm)	7.20	8.10	19.0	28.5	1.70	11.4
Chloride*	2.35	1.12	1.35	10.0	20.0	0.75
Asbestos+	3.00	208	23.0	45.0	110	9.00
Total Solids*	21.00	10.75	20.47	48.25	75.89	75.25
Total Volatile Solids*	31.00	7.94	8.98	22.25	1.17	55.31
Moisture*	79.00	89.25	79.53	51.75	24.11	24.75

* Values reported as percent by wet weight.
+ Fibers/100 gram.

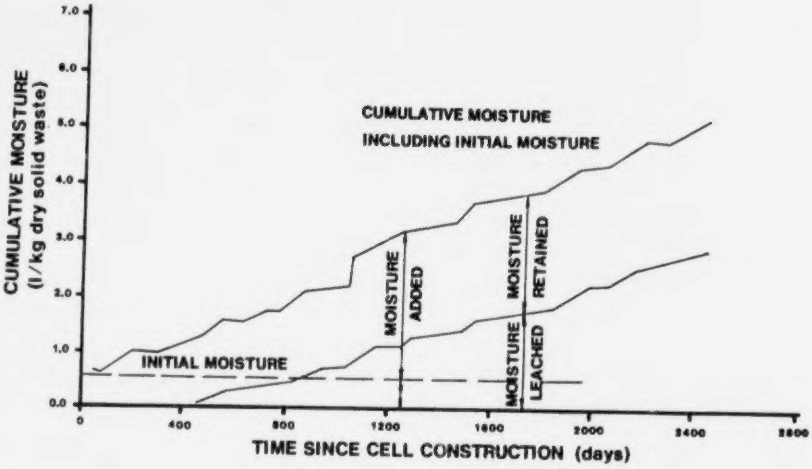

Figure 3. Moisture Balance for Cell 2.

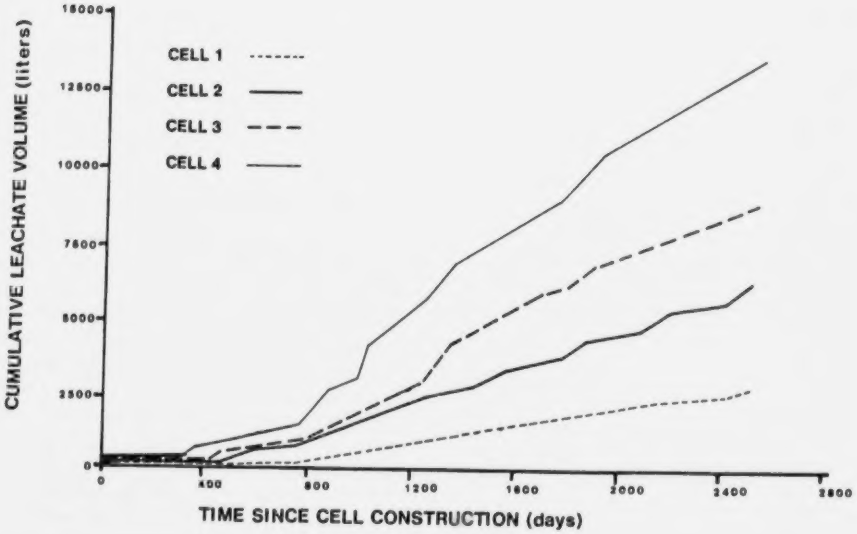

Figure 4. Leachate Volumes vs. Infiltration Rate.

TABLE 7. MOISTURE BALANCE SUMMARY

Test Cell	Loading Variable	Annual Infiltration		To Continuous Leaching			To 12/31/81	
		mm	Liters/kg	No. of Days	Initial Moisture (L/kg)	Moisture Retained (L/kg)	No. of Days	Moisture Retained (L/kg)
2	Control	406.4	0.577	476	0.62	1.43	2,596	2.16
4	Control	812.8	1.150	163	0.62	1.51	2,596	2.87
9	Petroleum Sludge	406.4	0.443	680	0.88	1.45	2,460	1.62
10	Battery Waste	406.4	0.479	218	0.93	1.13	2,460	1.52
12	Electroplating Waste	406.4	0.501	163	0.99	1.38	2,596	1.32
13	Inorganic Pigment Waste	406.4	0.419	224	0.74	1.11	2,596	1.41
14	Chlorine Prod. Brine Sludge	406.4	0.313	163	0.48	0.72	2,596	0.78
17	Solvent-Based Paint Sludge	406.4	0.348	476	0.50	1.01	2,596	0.97

continuous leaching and after seven years of monitoring. The annual applied infiltration is shown on a liters-per-kilogram basis to indicate that moisture input rates varied according to test cell loading variables. For instance, though most cells receive the same actual input rate (406.4 mm/year), they receive effectively different input rates when presented as a function of dry weight.

With the exception of Cell 9, the hazardous codisposal cells began to leach at earlier dates than the control cell (No. 2) and retained less moisture (lowered field capacity) at the time of continuous leaching. The low field capacities of these test cells are partially due to the inability of the waste additives themselves to retain moisture. Thus, in Test Cells 14 and 17, where proportionately larger quantities (dry weight basis) of wastes were added to the refuse, the overall field capacities are generally lower since moisture retained is determined on a liters/dry weight kilogram basis.

After field capacity has been achieved, one liter of moisture should theoretically be leached for each one liter of moisture added (i.e., input = output). Thus, the moisture retained should stabilize after the onset of continuous leaching. As indicated in Table 7, several test cells show stable field capacities after seven years. However, this moisture retention value increased significantly for the control cells and certain industrial waste additives. Notably, Test Cell 2, containing only municipal refuse, increased its moisture retention to 2.16 l/kg from 1.43 l/kg.

The effect of channeling is one possible reason for the field capacity increases. Channeling exists when moisture added to a waste percolates directly through it, failing to fill all the voids before leaching. Some voids which remain in the waste at the onset of continuous leaching may have gradually filled with moisture over time. The simulated landfills do not behave theoretically and some downward movement of moisture occurs before field capacity is attained in a particular refuse layer. Thus, field capacity was assumed prematurely for some cells and thought to be attained prior to actual field capacity.

Leachate Composition

Summaries of leachate quality analyses are presented in Figures 5 through 24. More than seven years of leachate data have produced significant and predictable trends for many parameters. Due to the extensive leachate quality data base, concentration histories are evaluated for both the exterior control test cells (Nos. 1, 2, 3, and 4) and the hazardous waste additive cells (Nos. 9, 10, 12, 13, 14, and 17). As previously discussed, the municipal solid waste cells receive different infiltration rates and thus provide an indication of the effects of moisture exchange on basic landfill behavior and decomposition. The supporting figures express parameter concentration as a function of cumulative leachate volume. The horizontal axis is in cumulative liters of leachate per kilogram of dry solid waste and serves to normalize the various test cells by accounting for the different loading densities. Since all the cells have identical depths and volumes, and similar densities of compacted refuse and computed field capacities, the summation of leachate volumes is related directly to the number of moisture exchanges in each simulated landfill. That is, when the amount of leachate collected, by weight (liter = kilogram), equals the amount of solid waste (dry weight) present in the test cell, then one moisture exchange has passed through that cell. In subsequent Figures 5 through 24, the x-axis refers to the number of moisture exchanges through the waste mass since historical leachate concentration changes are probably more related to leachate volume collected (or moisture exchanges) than to time.

The introduction of industrial wastes into the solid waste test cells was an attempt to provide empirical information on the practice of codisposing refuse and selected industrial wastes. Chemical composition of the six wastes (petroleum sludge, battery waste, electroplating waste, inorganic pigment waste, chlorine production brine sludge, and the solvent-based paint sludge) at the time of loading indicated that these wastes contained significant amounts of metals and other potential pollutants. Thus, leachate loadings of pollutant levels were expected to be higher for these cells relative to controls.

Leachate pH for all cells generally remained in the 5.0 to 6.5 range throughout the study period. Levels were basically unaffected by waste loading additives with the exception that some industrial waste cells had pH levels slightly above the municipal refuse cells. Early in the project, leachate pH appeared somewhat erratic followed by slow prolonged rises with time. However, several cells showed distinct rises to the range of 6.8 to 7.2, optimal for vigorous anaerobic activity. In particular, the interior test cells attained optimal pH levels which may be attributed to the higher test cell temperatures and thus, greater biological activity.

Figure 5 presents leachate pH for test cells receiving proportional infiltration rates. Initial levels dropped to about 5.0 to 5.25 in the four cells and gradually increased to 5.5 for Cells 1 and 2, and to about 6.8 for Cell 3. Test Cell 4, which receives the greatest infiltration rate (813 mm/yr), exhibited a similar increasing slope to pH 6.3. This trend of increasing pH is an important indicator of stable anaerobic decomposition and the lessening influence or build-up of volatile acids within the system. Adequate buffer capacity is obviously present in Cells 3 and 4 and appears to be a function of approximately 4 moisture exchanges (horizontal axis). The pH levels in Cell 4 are somewhat less than expected and may indicate a dilution of the buffering system. This dilution effect is supported by the field capacity calculations presented in Table 7. In upcoming years, pH levels are expected to increase substantially in Cells 1 and 2 as decomposition continues as a function of moisture exchange.

The chemical oxygen demand was determined on monthly samples from the test cells and no discernable trends could be noted to distinguish effects between the municipal refuse controls and the cells containing industrial waste additives. COD concentrations declined from initial peak values of over 60,000 mg/liter to relatively low levels (less than 15,000 mg/liter).

Figure 6 illustrates concentration release plots for COD in Cells 1, 2, 3, and 4. As shown, initial COD levels were quite varied, ranging from 60,000 mg/liter to 90,000 mg/liter. Patterns for COD declines appear exponential and relative to moisture exchanges through the test cells. At about 5.0 cumulative leachate volumes, leachate strength as measured by COD levels is greatly diminished (250 mg/liter).

Alkalinity is a measure of the leachate's capacity to neutralize acids. Leachate alkalinity concentrations exhibited the repetitive trends seen for other leachate parameters of significant declines from early peak levels at the time of field capacity. Alkalinity levels were not influenced by the various industrial wastes (in Test Cells 9, 10, 14, and 17).

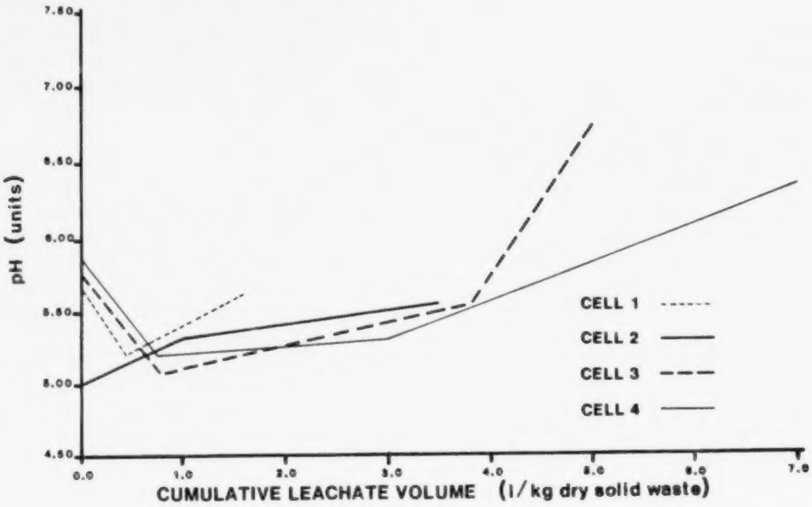

Figure 5. Leachate pH vs. Infiltration Rate.

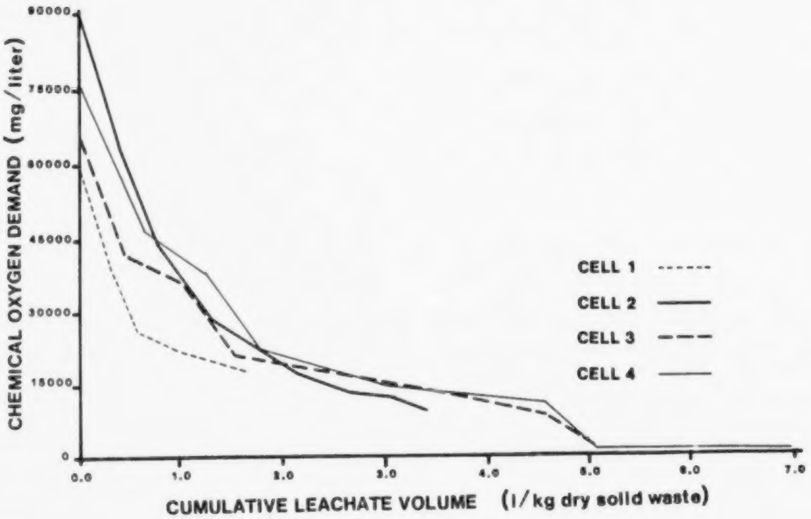

Figure 6. Leachate Chemical Oxygen Demand vs. Infiltration Rate.

However, alkalinity levels were slightly higher for the electroplating waste (Cell 12) and slightly lower for the inorganic pigment waste (Cell 13). Generally, concentration histories of the industrial waste test cells showed greater alkalinity fluctuations than the other test cells.

Figure 7 presents alkalinity concentrations for Cell Nos. 1 through 4 and indicates similar patterns with respect to moisture exchanges through the refuse mass. Test Cell 4 declined to stable alkalinity concentrations (about 3,000 mg/liter) after only 3.0 moisture exchanges and may support the fact that the buffer capacity of this cell was partially washed out by the high infiltration rate. At the end of the current monitoring period, Test Cell 1 remained at the highest alkalinity level of these control cells due to attaining only 2.0 cumulative leachate volumes (l/kg) since November 1974.

Leachate samples were analyzed monthly for Kjeldahl nitrogen and results are illustrated in Figure 8. Similarly-timed peak concentrations were recorded for the four cells (at field capacity), but peak values of TKN were less for Test Cell 1 at 1,350 mg/liter. TKN concentration histories shown in Figure 8 indicate that the release of TKN is a function of moisture exchanges through the refuse mass rather than time. At the end of the monitoring period, Test Cell 1 shows high TKN levels relative to Test Cells 2, 3, and 4. After about 6.0 moisture exchanges, TKN concentration in Cell 4 stabilizes at 20 mg/liter. As decomposition progresses, Cells 1, 2, and 3 are expected to show similar behavior.

Leachate iron measurements were conducted for the control and hazardous waste additive test cells throughout the seven year monitoring period. The concentration histories for leachate iron are shown in Figures 9, 10, and 11 and indicate great variations among the test cells. Of the major leachate quality parameters studied on this project, iron alone did not exhibit the same general peaking (at field capacity) and gradual concentration declines with cumulative moisture throughout. Instead, iron concentrations increased, decreased, or remained stable as a function of test cell additives and waste decomposition.

Figure 9 depicts iron concentration histories for Cells 1, 2, 3, and 4 and provides a perspective of the variability of the iron data. Generally, iron levels in these cells are stable to slightly increasing and range from 200 mg/l to 700 mg/l. Test Cells 1 and 3 show similar behavior and differ from the patterns shown in Cells 2 and 4. The variable behavior may be partially due to pH levels. As shown earlier in Figure 5, pH levels were also slightly increasing in Cells 1 and 3.

Figures 10 and 11 illustrate leachate iron levels found in the control (Cell 2) and the six industrial waste cells. Levels found in the battery waste cell (No. 10) were similar to Cell 2. The other five codisposal cells show elevated iron values and erratic release curves. Cells 9 (petroleum sludge), 12 (electroplating waste), 13 (inorganic pigment waste), and 14 (chlorine production brine waste) all show increasing iron concentration released in the leachate as cumulative moisture throughput increases. Additional influences on long-term iron release patterns from the test cells need to be evaluated.

Plots for leachate cadmium levels are shown in Figure 12, 13, and 14. Most of the test cells behaved similarly, with characteristic peak concentrations at field capacity reaching 0.30 mg/liter. Rapid declines in cadmium concentrations were also apparent as ultimate levels were in the low parts per billion (less than 0.05 mg/l). Figure 12 is presented for the exterior control cells receiving low to high water infiltration rates (Cells 1, 2, 3, and 4). As shown, the plots are characteristic of numerous leachate parameters. Cadmium concentrations are not clearly a function of cumulative leachate volume or of actual time. Peak concentrations are significantly lower for Cells 1 and 2 and thus these cells attain low cadmium values rapidly. However, Test Cells 2, 3, and 4 appear to stabilize (level out) at about 3.0 moisture exchanges. Since most cadmium levels in the leachate remain above the recommended drinking water standard of 0.010 mg/liter, further monitoring of the test cells is needed to assess the release patterns of cadmium at low levels.

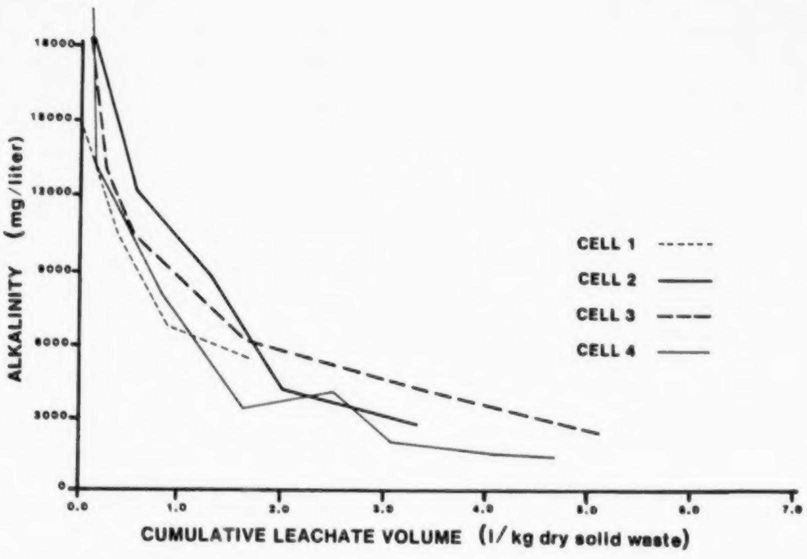

Figure 7. Leachate Alkalinity vs. Infiltration Rate.

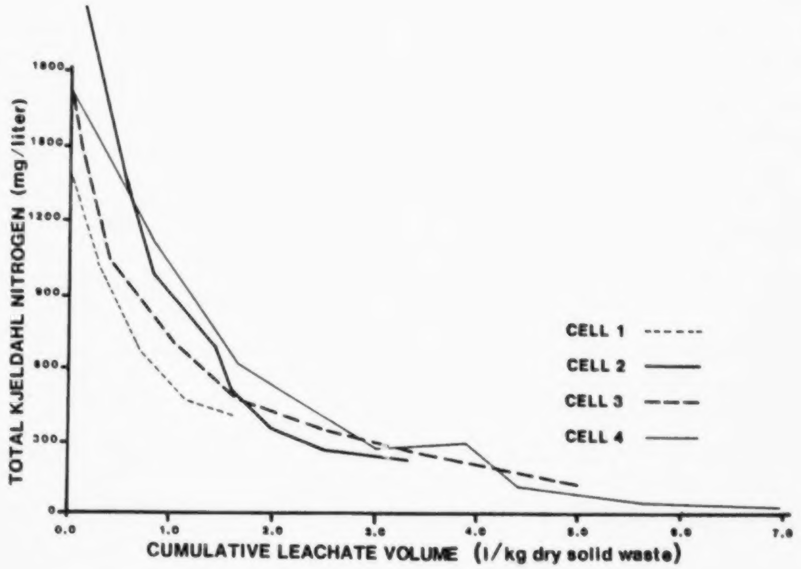

Figure 8. Leachate Kjeldahl Nitrogen vs. Infiltration Rate.

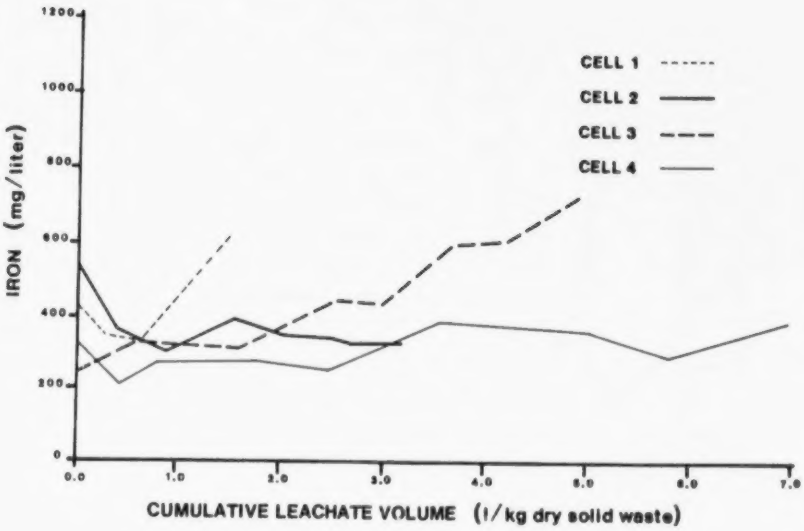

Figure 9. Leachate Iron vs. Infiltration Rate.

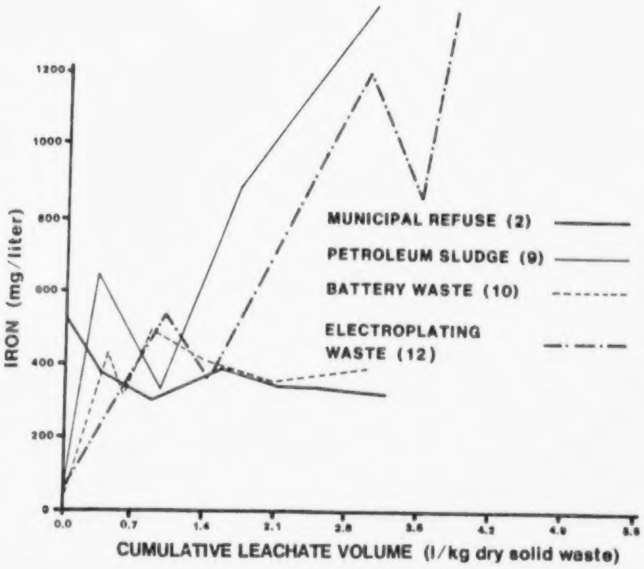

Figure 10. Leachate Iron for Industrial Waste Cells.

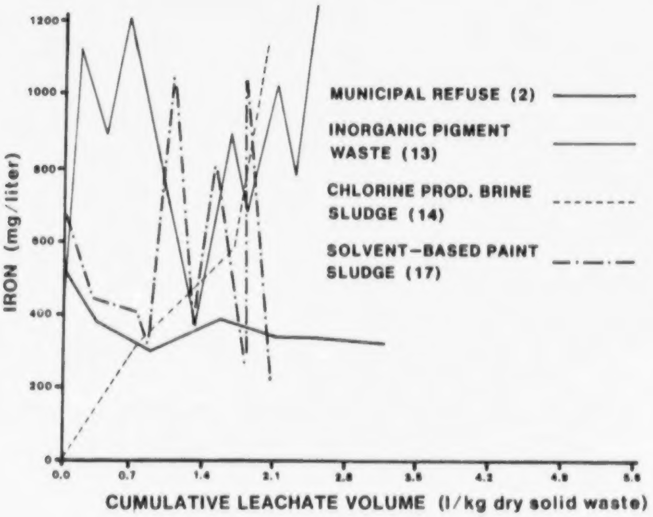

Figure 11. Leachate Iron for Industrial Waste Cells.

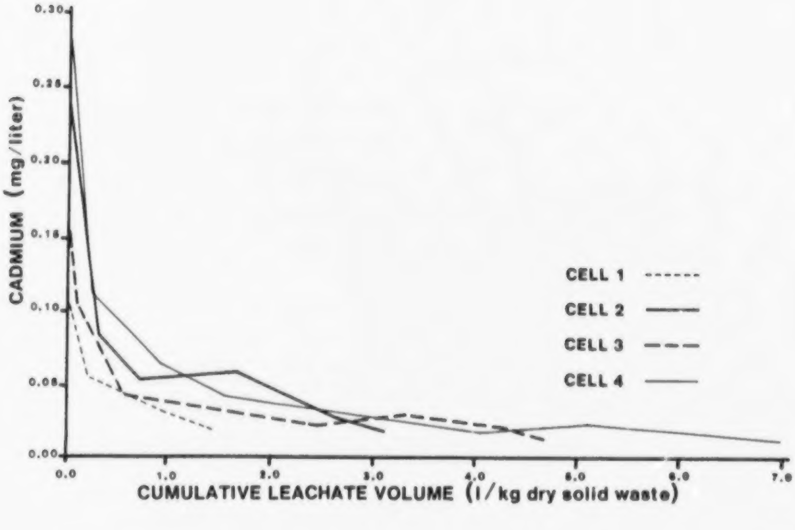

Figure 12. Leachate Cadmium vs. Infiltration Rate.

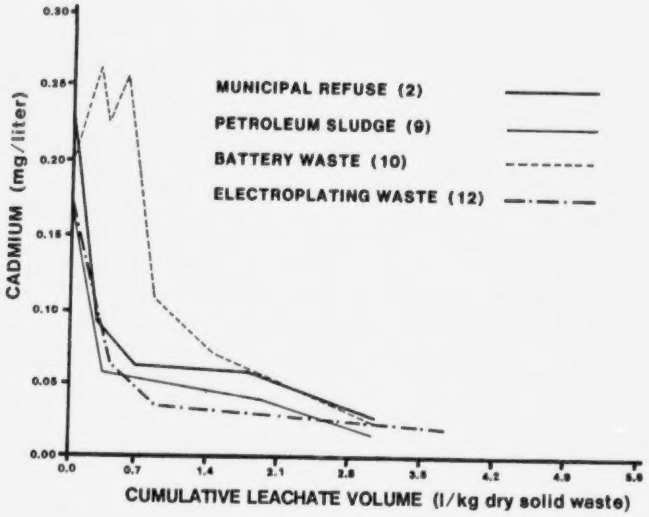

Figure 13. Leachate Cadmium for Industrial Waste Cells.

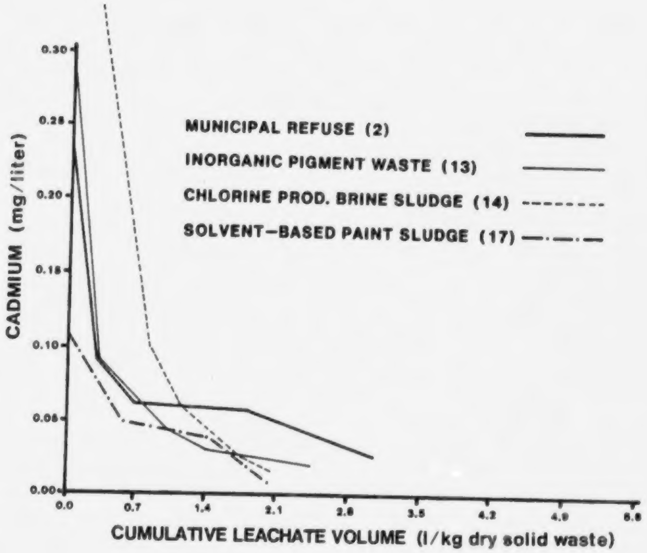

Figure 14. Leachate Cadmium for Industrial Waste Cells.

Figures 13 and 14 present leachate cadmium results for the same industrial waste cells and cadmium concentration histories behaved similarly to the control (Cell 2). Only the battery waste cell (No. 10) and the chlorine production brine sludge (No. 14) appeared to significantly differ. Results for these two cells indicate that greater cadmium levels were found from the time of continuous leaching to about 1.4 cumulative leachate volumes. Current cadmium levels for all industrial waste cells are below 0.030 mg/liter.

Leachate nickel was measured for the seven year monitoring period and the data indicated similar concentration histories for most of the test cells. With two exceptions, all the cells resembled the plot for Test Cell 2 (control), shown in Figures 15, 16, and 17. Peak concentrations were predictably at field capacity and ranged from about 2.0 mg/liter to 3.0 mg/liter. Nickel concentrations quickly declined in the leachate samples to about 0.2 mg/liter after 3.0 cumulative leachate volumes.

Leachate nickel concentration presented in Figures 16 and 17 indicate some differences according to test cell additives. As might be expected, the electroplating waste (Cell 12) contributed the greatest amount of nickel into the leachate solution. Peak levels attained were highest in this cell and in Cell 14, containing the chlorine production brine sludge. All nickel plots show steep concentration declines from initial high levels, characteristic of landfill leachate behavior. The remaining cells (Nos. 9, 10, 13, and 17) were roughly similar to the plot for Cell 2.

Further studies are needed to assess influences from industrial additives on landfill behavior. Certainly, dramatic increases in leachate concentrations as contributed by industrial wastes will affect leachate treatment designs. However, for all leachate parameters monitored in this study, industrial waste influences on leachate concentrations were always less than one order of magnitude. This relationship occurred even in the chlorine production brine sludge cell (No. 14) and the solvent-based paint sludge (No. 17), where the industrial additives were loaded at approximately 40 percent (dry weight basis) of the total waste mass within the cells.

LEACHATE MODELING

Qualitative trends of landfill behavior in simulated landfills have been well documented by various researchers [1, 2, 3, and 4]. However, the quantitative prediction of leachate composition and contaminant release can provide a more useful description of the ongoing processes of solid waste decomposition and provide an important method for forecasting leachate strength and potential ground water hazards. Recent efforts [5, 6, 7, 8, and 9] have yielded conceptual mixed reactor models which mathematically describe leachate behavior in simulated landfills. The purpose of this section is to assess the semi-empirical equation developed by Wigh [7] using leachate composition data from the Center Hill project. As part of this evaluation, Test Cell 4 is mathematically described for eleven leachate parameters to demonstrate that the equation can provide a good approximation of leachate quality for simulated landfills.

Wigh's equation is based on two first order reactions and expresses contaminant concentration as a function of cumulative leachate volume, maximum concentration, and two rate constants. The general predictive equation describing the concentration change with time is:

$$C = C_o e^{-(q/V - k)t}$$

Modification of Wigh's equation allows the expression of contaminant concentration as a function of moisture throughput, or cumulative leachate volume:

$$C = C_o e^{\frac{-(q/V - k)t}{q}}$$

Where: C = concentration
C_c = maximum concentration
e = mathematical constant
q = leachate flow rate (1/kg/yr)
V = volume of water in the refuse at field capacity (1/kg)
k = empirical rate constant (yr)
t = cumulative leachate volume (1/kg)

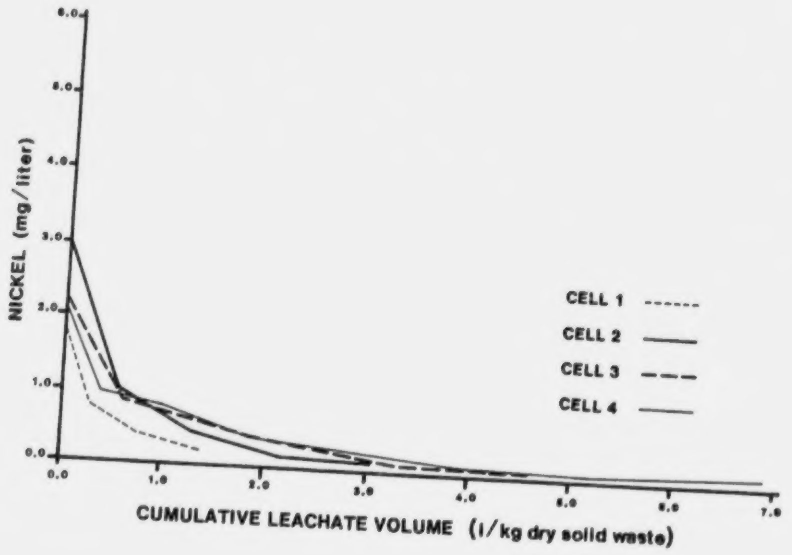

Figure 15. Leachate Nickel vs. Infiltration Rate.

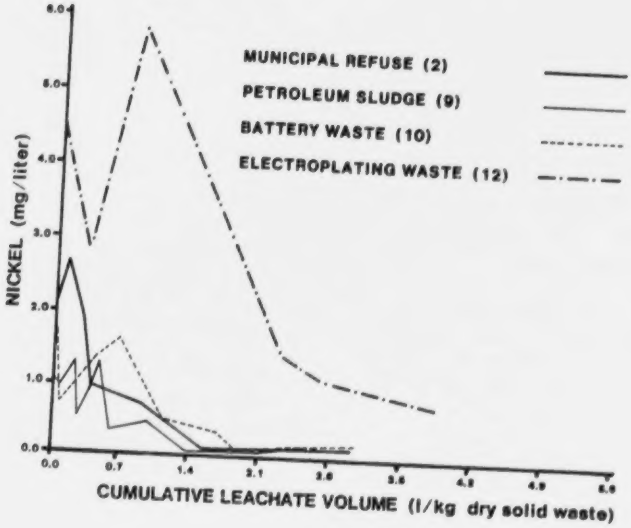

Figure 16. Leachate Nickel for Industrial Waste Cells.

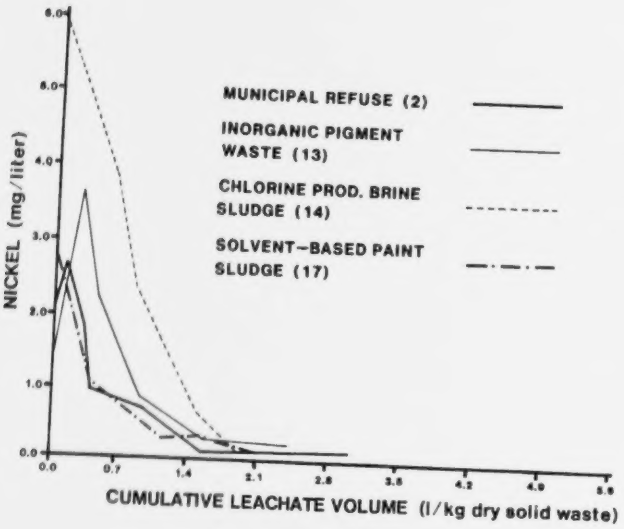

Figure 17. Leachate Nickel for Industrial Waste Cells.

This leachate modeling effort is based on the above predictive equation. For the parameters monitored in this project, most peak concentrations were measured at the time of continuous leaching. Therefore, the value for C_0, selected as the maximum concentration, usually occurred at the time of field capacity. A careful determination of C_0 is necessary. Initial leachate concentrations (at the time of continuous leaching) may be highly variable and extreme values may bias the model. In addition, this approach assumes that C_0, the maximum concentration, occurs at initial leaching. This assumption allows the model to capture the general decrease from high concentration changes.

The leachate flow rate, q, is assumed to be constant with time and is determined by plotting cumulative leachate volume versus time for the specific test cell. Figure 4 graphically plots total leachate generation for Cell 4. The slope of the plot was obtained by least squares analysis to provide the empirical constant, q, in liters/kilogram dry refuse/year. From this procedure, q was determined to be 1.17 liters/kg/year.

V was calculated for Test Cell 4 from initial moisture contents and field capacity determinations as previously shown in Table 7. V is the total moisture retained in the test cell at field capacity divided by the total kilograms of dry refuse as loaded into the test cell. As noted in Table 7, moisture retention values for Test Cell 4 increased during project operation. Thus, the value V may range from 1.51 to 2.87 liters/kilogram. For this current modeling effort, V was selected at 1.51 liters/kilogram dry weight.

The empirical rate constant, k, was determined by the following procedure for each modeled leachate parameter. A straight line equation was developed by applying the log function to both sides of the modified predictive equation. From this, the slope of the line becomes $-(q/V - k)/q$, which can be solved by least squares regression analysis. That is, the log of concentration (C) is plotted against cumulative leachate volume on the x-axis. With the slope determined and since q and V are known, k is determined by subtraction, where:

$$k = \text{slope}(q) + (q/V)$$

Determination of the predicted leachate concentration history curve for a given parameter becomes straightforward. The appropriate C_0, q, V, and k values are established for a specific test cell and development of the predictive concentration, C, is by cumulative leachate volume data points.

Comparison of the predictive equation with the actual concentration histories measured in Test Cell 4 are shown in Figures 18 through 28. Test Cell 4 receives the highest water infiltration rate, and therefore, has the most developed concentration curves. Reasonably good fit to the data is evident except for total phosphorus (Figure 22), total solids (Figure 24), and iron (Figure 25). For both total phosphorus and total solids, the curve for the predictive equation yielded high estimates for leachate concentrations when compared with actual results. Conversely, leachate iron in Test Cell 4 remained significantly above the predictive curve through 7.0 cumulative leachate volumes.

Computed rate equations are listed in Table 8 for each of the parameters in Figures 18 through 28. The first order equations can be used to determine the predicted leachate strength at any given cumulative leachate volume.

SUMMARY

This project simulated the decomposition of landfilled municipal solid waste and tested effects on that decomposition process due to the addition of calcium carbonate, sewage sludge, and industrial wastes to specific test cells. In previous lysimeter studies, decomposition patterns are most frequently measured by leachate composition since the repetitive shape of leachate concentration curves has been well documented. For the Center Hill project, comparable results are reported for leachate parameters as well as for gas composition and generation.

More importantly, though, the experimental program at Center Hill is unique in its attempt to demonstrate landfill behavior. The uniqueness of the research experiment has developed because it contains the following:

- Long-term monitoring effort
- Controlled moisture input/output program
- Extensive analytical efforts, both initial and ongoing
- Sufficient control cells
- Duplicate test cells
- Cells constructed to measure gas production
- Nutrient (sludge) and buffer addition
- Industrial waste codisposal

Each of the above serve to provide a progressive understanding of the processes that occur within a sanitary landfill and a better assessment of the related environmental effects. The interim results presented in this paper address the timing of leachate stabilization under controlled conditions, and determine some

TABLE 8. RATE EQUATIONS FOR TEST CELL 4.

Parameter Rate Equation*	Units	Rate Constant, k
Specific Conductance = $17{,}500e^{-0.276t}$	microsiemans	0.45
COD = $75{,}000e^{-0.72t}$	mg/liter	0.07
TOC = $30{,}000e^{-0.64t}$	mg/liter	0.03
Alkalinity = $13{,}000e^{-0.33t}$	mg/liter	0.39
Total Phosphorus = $325e^{-0.56t}$	mg/liter	0.12
TKN = $1{,}700e^{-0.53t}$	mg/liter	0.15
Total Solids = $55{,}000e^{-0.44t}$	mg/liter	0.26
Iron = $210e^{-0.09t}$	mg/liter	0.67
Zinc = $100e^{-1.3t}$	mg/liter	0.75
Cadmium = $160e^{-0.44t}$	ug/liter	0.26
Nickel = $1.9e^{-0.53t}$	mg/liter	0.15

* Rate equation constants based on cell-specific conditions.
t = Cumulative leachate volume (liters/kilogram dry solid waste).

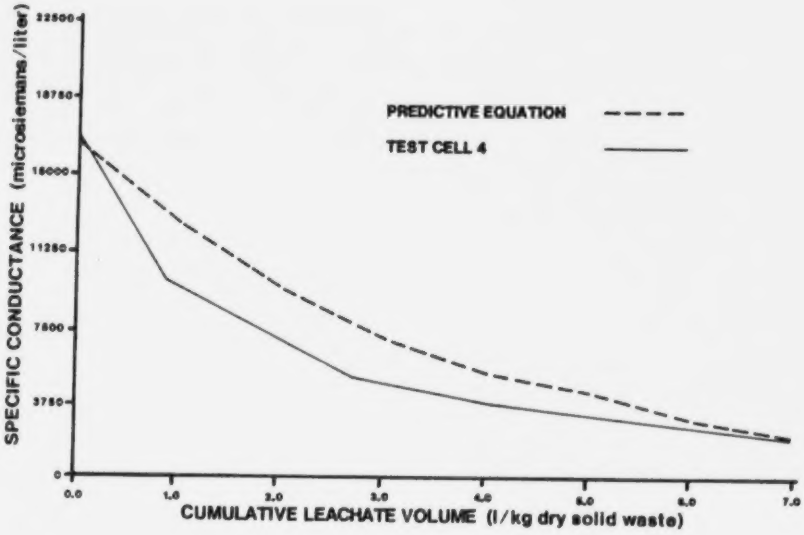

Figure 18. Predicted Specific Conductance Concentration.

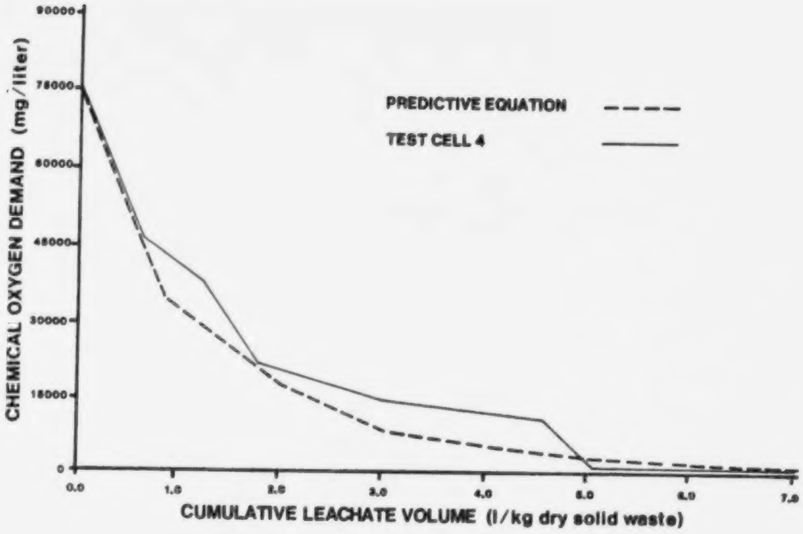

Figure 19. Predicted COD Concentration.

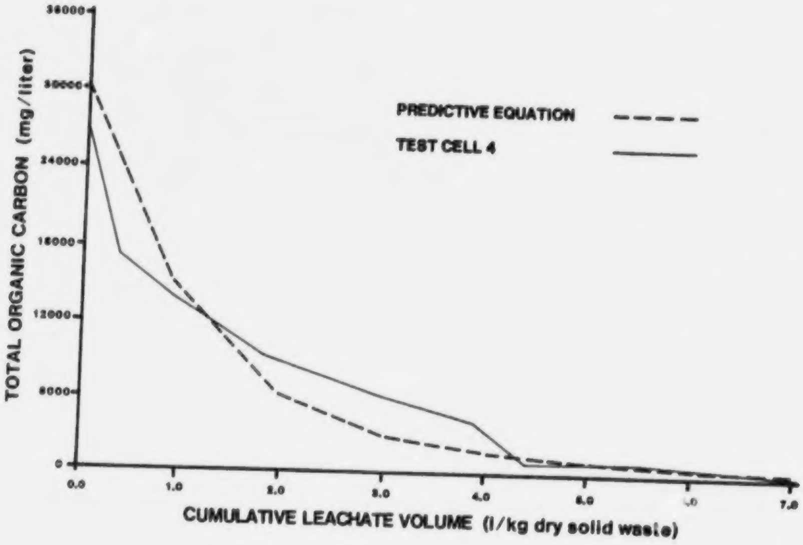

Figure 20. Predicted TOC Concentration.

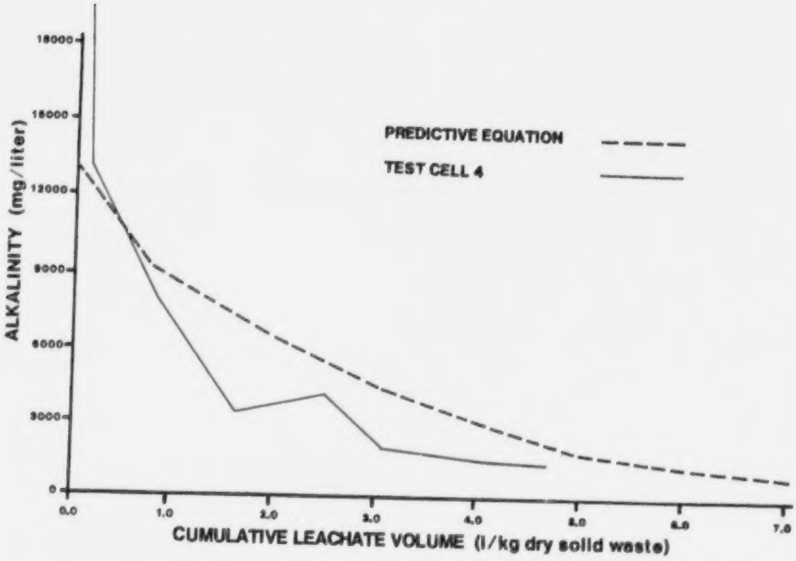

Figure 21. Predicted Alkalinity Concentration.

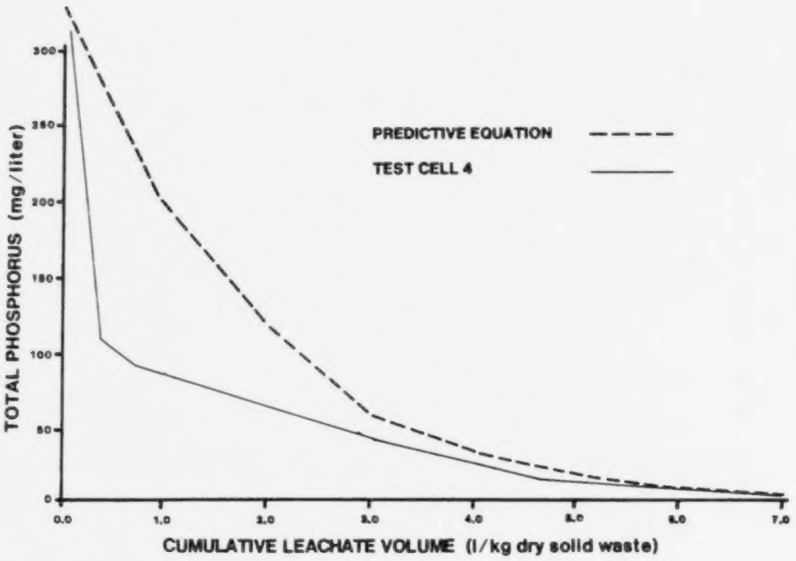

Figure 22. Predicted Total Phosphorus Concentration.

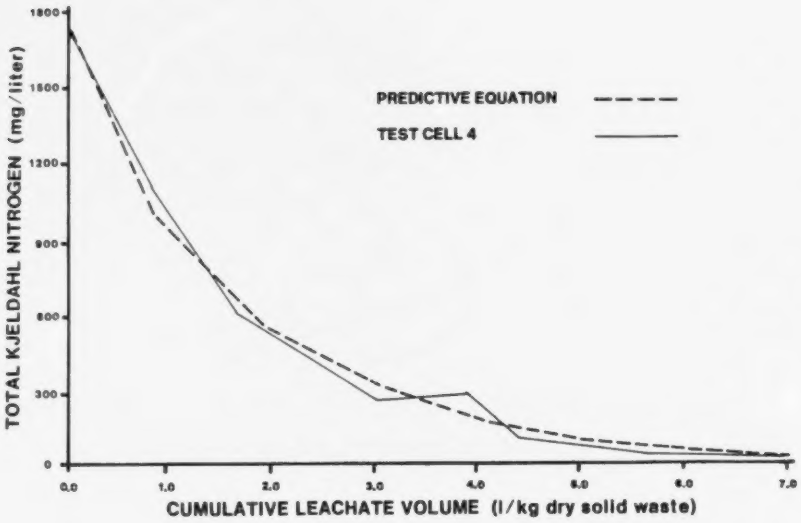

Figure 23. Predicted TKN Concentration.

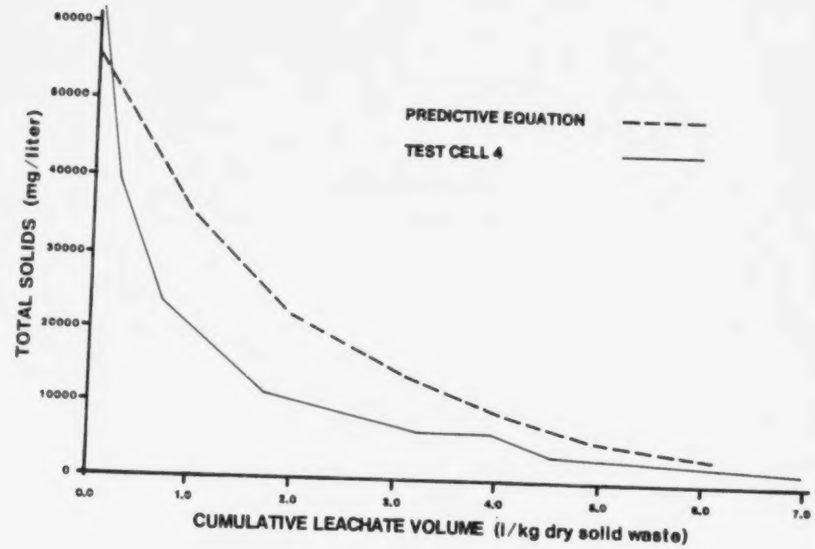

Figure 24. Predicted Total Solids Concentration.

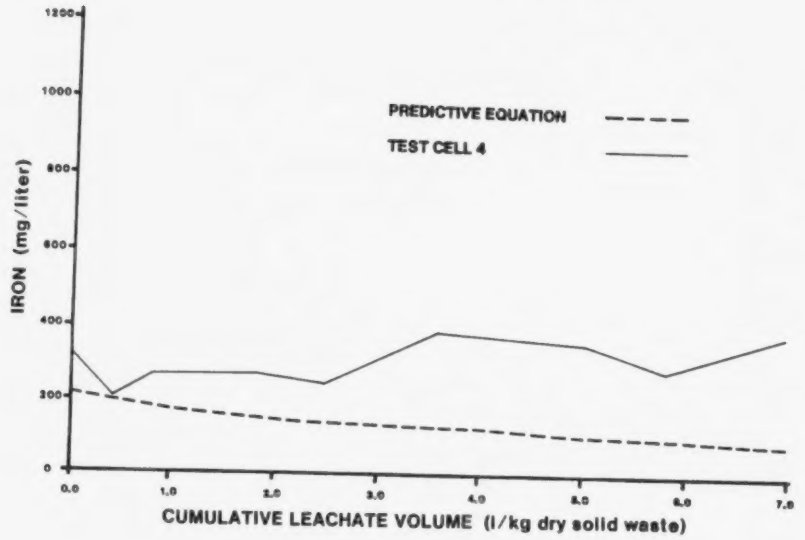

Figure 25. Predicted Iron Concentration.

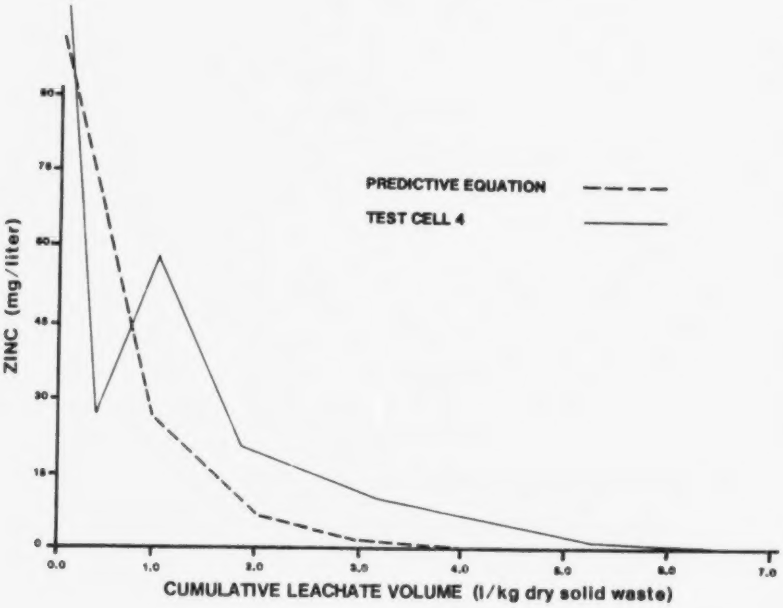

Figure 26. Predicted Zinc Concentration.

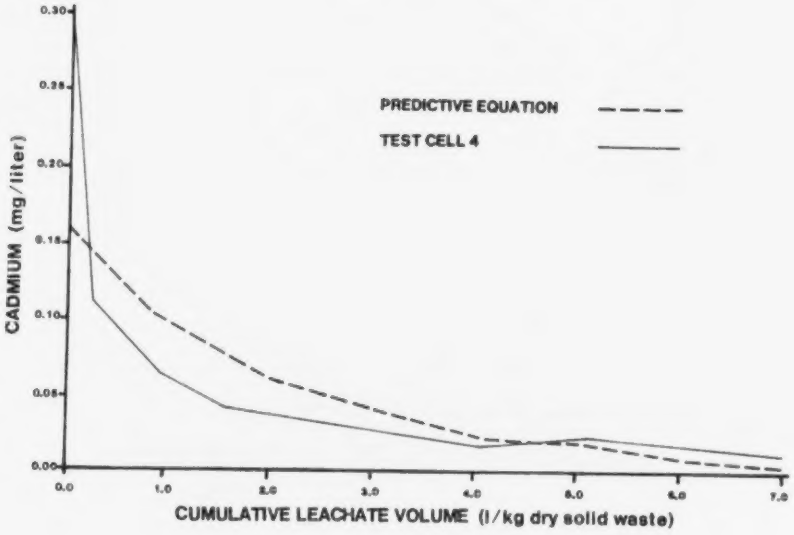

Figure 27. Predicted Cadmium Concentration.

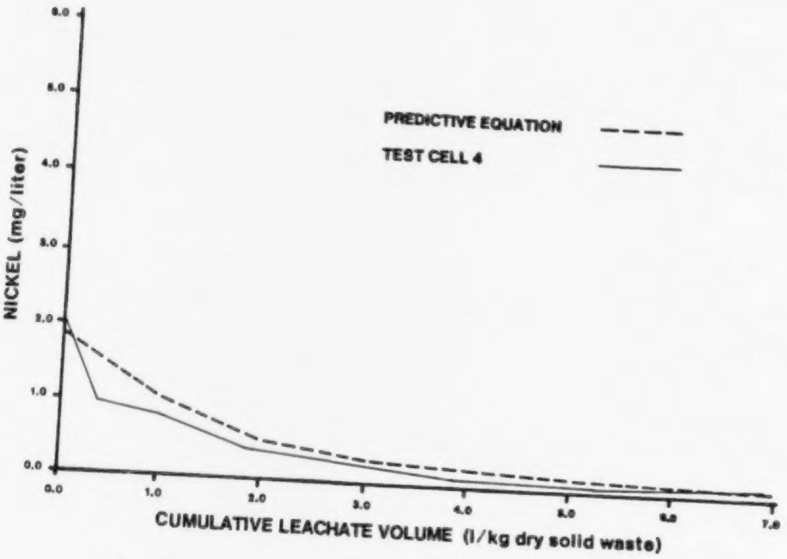

Figure 28. Predicted Nickel Concentration.

of the long-term impacts associated with the disposal of selected hazardous wastes into municipal solid waste. An evaluation of current findings is presented below:

1. Leachate quantities collected from six hazardous waste codisposal cells and municipal refuse control cells indicated that codisposal cells produce leachate at earlier dates than the control cell, and that the codisposal cells retain less moisture (lowered field capacity) for the duration of the study period. These results suggest that precipitation will not be as readily retained in an actual codisposal landfill for wastes having physical characteristics similar to those used in this study, and that earlier leachate production should be expected.

2. Long term leachate concentration histories for comparing cell performances were expressed as a relationship of cumulative leachate volume rather than time. Concentrations of metals (e.g., iron, cadmium, and nickel) were higher in leachates from industrial waste codisposal cells but leachate strength, as measured by COD, pH, and alkalinity, was similar for the codisposal and municipal refuse control cells. Iron behaved differently than other leachate constituents and showed gradual increases in concentration during the study period for the municipal refuse control cells. For codisposal Cells 9, 10, 13, 14, and 17, iron concentrations remained significantly higher over the controls.

3. Leachate concentrations generally peaked within a few months of the achievement of field capacity. Typical for many of the parameters was the peak concentration occurring at field capacity, followed by slow declines thereafter. This occurrence of initial peak concentrations in conjunction with earlier leachate production in hazardous waste codisposal test cells suggests that on-site leachate treatment systems for codisposal landfills should be capable of receiving the high strength leachates during the early stages of landfill operation.

4. The controlled moisture infiltration/leachate collection program coupled with the extensive leachate quality data base has provided empirical evidence that leachate strength decreases as a function of moisture exchange through the refuse. Since

leachate strength is a primary indicator of landfill stabilization and decomposition, the data show that the initial loading of the six industrial hazardous waste did not significantly impact the decomposition of municipal refuse.

5. Test Cell 14 (chlorine production brine sludge) exhibited higher peak concentrations and elevated leachate concentration histories most often among the six industrial additive cells.
6. Long term leachate concentration trends were developed for Test Cell 4 which received the greatest amount of infiltration (813 mm/year). A semi-empirical model, incorporating parameters for the major factors influencing landfill decomposition and leaching, was calibrated with data from Test Cell 4. The validity of the model will be tested with data from other test cells and should be tested against comparable field data.

Further efforts as part of this research program will include expansion of applied forecasting techniques. The quantitative prediction of leachate composition and contaminant release can provide a more useful description of the ongoing processes of solid waste decomposition and provide important methods for forecasting leachate strength and potential ground water hazards. Further batch-type predictive techniques will be developed which rely not only on moisture flow through the refuse mass, but also on dilution/mixing and fundamental transport phenomena which occur within the landfill environment.

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APPLICATION OF SOLIDIFICATION/STABILIZATION TECHNOLOGY TO ELECTROPLATING WASTES

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ABSTRACT

Electroplating wastes are generally composed of fine-grained metal hydroxides generated from the treatment of spent plating baths, rinse water, and liquid from cleaning and etching operations. A number of solidification/stabilization systems have been applied to these residues in order to develop a waste material with superior containment properties. Systems for developing new, high-temperature, stable chemical compounds have found application for immobilization of specific metals. Low-temperature silicate polymers provide a lower degree of containment. Organic polymer systems that do not involve acidification have proved to be beneficial. Thermoplastic encapsulation systems provide excellent containment. Analyses of water leachates from crushed pozzolan-Portland and pozzolan encapsulated materials showed higher concentrations of some metals than were obtained from water leaches of the untreated wastes. An X-ray diffraction study of pozzolan-Portland and pozzolan encapsulates indicates no crystal chemical involvement of the waste in the setting and hardening process. Containment in these materials comes from encasing the metal hydroxides in the cementitious matrix.

INTRODUCTION

Electroplating typically involves surface cleaning and surface etching, plating, and rinsing the plated parts. Each step generates a series of acid or alkaline solutions that contain potentially toxic metals in solution (such as cadmium, chromium, copper, nickel, lead, and zinc). The high metal concentrations are derived from spent processing solutions, rinse water or "drag out," cleanup from spilled materials, and corrosion of plating tanks and piping. Wastewater from an electroplating operation also can contain cyanides from stripping and plating and organic solvents, oil, and grease from stripping and metal cleaning operations.

The waste streams from plating operations are typically segregated and treated as three separate types of liquid wastes:

a) cyanide-containing wastes,

b) chromium-bearing waste,

c) acidic wastes.

The cyanide-containing waste are generally treated by alkaline chlorination to oxidize cyanide. The chromium-bearing solutions are acidified and treated with $FeSO_4$, SO_2, or $NaHSO_4$ to reduce chromium to the trivalent form. When reduction is complete the chromium is precipitated as $Cr(OH)_3$ using lime slurry. The acid waste stream is generally neutralized with lime. Each process generates a lime-neutralized metal hydroxide sludge that must be handled as a hazardous waste.

The Environmental Protection Agency has recently published new regulations to improve effluent quality from metal-finishing facilities (30). These regulations may be expected to increase the amount of sludge requiring disposal. Metal hydroxide sludges have generally presented problems in disposal due to the potential for dispersal and dissolution (4).

The purpose of this paper is to review the work to date on solidification/stabilization processes applied to electroplating waste (metal hydroxide sludges) and to point out technical problems and complications associated with handling these materials. The discussion in this paper will focus on the basic chemistry of electroplating waste and reactions involved in generic types of waste solidification and should not be interpreted as indicating the performance to be expected from any proprietary process. Proprietary processes frequently include specific adaptations of general solidification/stabilization systems discussed here and may perform very differently from the systems discussed.

Physical, Chemical and Minerological Characteristics of Electroplating Waste Sludges

The physical characteristics of a typical electroplating wastewater treatment sludge are summarized in Table 1. A typical grain size distribution is presented in Figure 1.

TABLE 1. PHYSICAL CHARACTERISTICS OF A TYPICAL ELECTROPLATING WASTEWATER TREATMENT SLUDGE

Characteristic	Value
% less than 200 mesh	95
Median grain size (mm)	0.015
Percent solids (%)*	36.7
Liquid limit (%)	107
Plastic limit (%)	58
Plasticity index (%)	49
USCS classification	MH
Specific gravity	2.70
Dry unit wt (kg/cu meter)	514.18
Void ratio	4.67
Coefficient of permeability (cm/sec)	1.69×10^{-5}

*Average of two.

The electroplating sludge samples reported in the literature generally have fine particle sizes, low permeability, low strength, and high compressibility (1). These properties generally make them undesirable for inclusion as aggregate in concrete where strength and grain size of

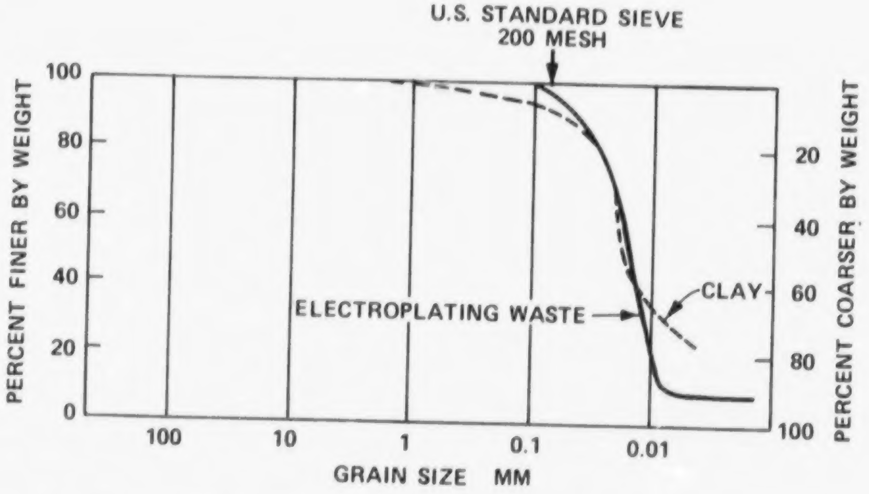

Figure 1. Grain size distribution of a typical electroplating waste sludge (after Bartos and Palermo, 1977).

aggregates must be regulated to assure that the aggregate does not prevent strength development.

In general, the percent of material passing 200 mesh must not be more than 3 percent of the total aggregate. Clay in lumps presents special problems in concrete and is often limited in specifications to 1 percent of the mix (12). Dewatered sludges typically have over 90 percent of the material finer than 200 mesh and contain lumps of clay-sized particles. They are unsuitable for use as standard aggregate, and make poor construction materials for dikes or embankments.

The chemical characteristics of several electroplating sludges are summarized in Table 2. These wastes are varying mixtures of fine-grained metal hydroxides along with salts from materials added to neutralize the liquid wastes.

X-ray diffraction examination of powder mounts of the sludge showed the characteristic diffraction peaks for gypsum ($CaSO_4 \cdot 2H_2O$) and traces of hydromica (clay) and quartz. The metal hydroxides are amorphous. No peaks for calcium hydroxide, a commonly-used neutralizing agent, were found. X-ray analysis of material that was leached for two years with distilled water saturated with carbon dioxide showed a slight decrease in diffraction peaks associated with the gypsum. The metal hydroxides remained amorphous and no formation of metal carbonates or other phase transformations were detected (15).

Solidification/Stabilization Techniques Employed with Electroplating Wastes

Electroplating wastes are a mixture, consisting primarily of amorphous metal hydroxides, that has a clay-like consistency. The majority of solidification/stabilization processes evaluated for the disposal of electroplating waste do not attempt to change the nature of the compounds in the sludge; they are intended to isolate the metal hydroxides from leaching

TABLE 2. CHEMICAL COMPOSITIONS OF ELECTROPLATING WASTEWATER TREATMENT SLUDGES

Sample Reference Constituent	A (25)	B (8)	C (28)	D (11)
As	460**	--	24	--
Be	0.25	--	840	--
Cd	38.5**	8000	1800	580
Cr	15600**	105000	150000	65000
Cu	100	32000	95000	100000
Fe	13700**	--	--	10000
Hg	23.0	--	0.53	--
Ni	35	10000	6100	--
Pb	267	--	1400	600
Zn	--	--	18000	7900
Cl	13500	--	--	--
CN	460	--	--	--

*All analyses are in mg/kg on a dry weight basis.

**Maximum concentrations observed in sludge samples analyzed.

water. Other processes attempt, with varying degrees of success, to produce new insoluble, durable compounds that retain the potentially toxic metals from leaching after shallow land burial. In some cases, especially where possible low-temperature silicate or carbonate reactions are involved, it is difficult to declare which chemical and physical mechanisms are involved. From the work done to date at Waterways Experiment Station and other laboratories, it is possible to reach some general conclusions as to the mechanism for waste containment and the applicability of different techniques to electroplating wastes.

Production of New Insoluble Compounds

A number of high temperature modifications of heavy metal (especially chromium) sludges have been reported by Inoue and others (10) and by Shoto and Hattori (23, 24), and Hattori, Shoto, and Nagaya (6). The formation of new crystalline phases has been documented using X-ray diffraction and solubility studies. Uvarovite ($Ca_3Cr_2Si_3O_{12}$) and Cr_2O_3 were found in X-ray diffraction patterns of solidified chrome plating wastes. For a complex waste containing cadmium, copper, nickel, lead, and zinc it may be necessary to develop a number of very specific silicates to provide carriers for the various metals. Containment would be very efficient if total chromium-to-garnet conversion were accomplished.

Rousseaux and Craig (21) reported testing a low-temperature silicate process for immobilizing heavy metals in electroplating wastes. The process involves the addition of a siliceous reagent to an acid ($pH = 1.5$) metal solution. The pH is then raised by the addition of caustic and a polymer forms. The polymer mixture is hardened with the addition of Portland cement. Extraction procedure testing showed that with the exception of cadmium, no heavy metals leached in excess of the regulatory criteria. The exact mechanism involved in this technique was not discussed although the process description indicates a new siliceous polymer is formed.

Formation of low temperature silicate polymers that may include heavy metals have also been suggested as possible immobilization systems in other processes involving mixing soluble silicates, electroplating wastes, and Portland cement (7, 22). Additional work is required to demonstrate the binding mechanisms involved in these systems.

Low temperature reactions between soluble silicates and metal salts (other than alkali metals) or metals in solution can generate a variety of precipitates that are non-crystalline, non-homogeneous, and difficult to characterize. When dissolved metal salts and soluble silicate are mixed, the composition of the precipitate depends on the proportions of the reactants available at the point of mixing. The composition of the first part of a precipitate differs from the last. Even if the pH is kept low during mixing to prevent metal hydroxide formation, the soluble silica will be continuously polymerizing and the proportion of metal bound to the silica depends on the extent of silica polymerization that occurs before the metal binding occurs. The metal content is even more poorly controlled if the pH is not kept low. Metal silicates precipitate at pH's only slightly lower than the pH for corresponding hydroxide formation, therefore, the reaction yields metal hydroxide or polymeric basic metal hydroxide that cannot combine in any orderly way with the precipitating silica. The resulting material may not contain any definite compounds and the metal hydroxides precipitate along with the silica by mutual coagulation (9, 31).

Disordered gel structures offer greater potential for ion migration than crystalline materials. Diffusion reactions in silica gel are a common method for production of specific crystalline compounds (5, 16). The binding of metals on the surface of silica gel is similar chemically to the bonding in hydroxocomplexes in metals. This has been shown by examining pH's at which various metals adsorb to silica gel surfaces. The pH drop for release of metals from silica gel treated waste may in part be related to the pH change required for adsorption. If this is so, the order of release with lowering pH for some of the metals would be Cd, Cu, Pb, and Fe. In the extractant analysis from Rousseaux and Craig (21) the concentration of the metals always follows the order Cd, Cu, and Pb in decreasing concentration, although this is not the order of concentrations in the waste

(Table 3). Dissolution of metal complexes on silica gel may be a major system of metal release in these silica gel materials.

Organic compounds (metal stripper or cleaners) are generally not compatible with concentrated soluble silicate solutions. Polar organic solvents can dehydrate or separate from an aqueous phase. In hydrophobic organic solvents, silicate solutions separate into the aqueous phases. A few organic compounds such as glycerin or ethylene glycol are miscible in silicate solutions (17). Organic components in electroplating waste would rarely be chemically bound in silica gel-based treated containment products.

Encapsulation Systems

Encapsulation systems used with electroplating wastes depend on the isolation of the metal hydroxide waste in some organic or inorganic matrix that prevents contact with the surrounding environment (especially surface water or groundwater). The scale of encapsulation and the materials involved are usually used to classify the treatment process as macro- or microencapsulation. The microencapsulation systems usually involve coating of individual particles of precipitate. Macroencapsulation involves coating large aggregates of particles as a single unit with a coating that is very much thicker than a single particle diameter.

The major macroencapsulation system that has been developed and tested with electroplating waste employs a fused polyethylene jacket on a core of polymer-cemented wastes. The proposed waste blocks would be on the order of one meter on a side with a 0.5 cm jacket (13). Two-year leaching tests conducted with the material have demonstrated its effectiveness.

Microencapsulation systems have been developed with a variety of materials, including organic polymers, thermoplastic materials, pozzolan-Portland cement mixtures, and pozzolan cements. Most microencapsulation systems do not involve any reaction between the matrix and the waste; although in the case of silicate-based systems this has never been completely

TABLE 3. COMPARISON OF CONCENTRATIONS OF SELECTED METALS IN BLENDED ELECTROPLATING WASTE AND IN EP EXTRACTANTS FROM SILICATE POLYMER TREATED BLENDED ELECTROPLATING WASTE*

Calculated Concentration in Blended Electroplating Waste			
	Cd	Cu	Pb
Untreated Waste	2890**	7100	1710
Concentrations Found in EP Extracts from Treated Blended Waste			
Run No.			
1	5.60	0.28	0.013
2	2.30	0.64	0.016
4	0.10	0.06	0.006
5	2.70	0.36	0.017

*From Rousseaux and Craig (21).

**All values are in mg/liter.

demonstrated and reactions between waste and pozzolan have been considered possible.

Organic polymer solidification systems were originally developed for nuclear waste disposal and in some cases require that acidic reagents be used to initiate polymerization (for example, urea-formaldehyde systems). For some wastes this is not a problem; but it is with metal hydroxide wastes. Testing done with systems where the sludge pH was lowered to 2.8 has demonstrated that a major loss of metal hydroxide waste occurs (15). Other problems with organic polymer encapsulation systems can result from undesirable oxidation-reduction reactions between wastes and any water soluble polymerization promoters and initiators used in the system. In polyester-based systems promoters are reducing agents (such as cobalt naphthenate) that can react with any chromate (Cr^{+6}) present in the plating waste. Initiators are commonly strong oxiders such as methyl ethyl peroxide or hydrogen peroxide that oxidize reduced metals (especially Cr^{+3}) in the waste. Undestroyed cyanide in electroplating wastes was found to complex metals in the polymerization promoter (cobalt naphthenate) used in a polyester system that was tested. This complicated the polymerization process and additional promoter was needed to complete solidification (26, 27).

Thermoplastic microencapsulation systems contain the solid particulate waste by mixing the sludge in a heated polymeric material, such as asphalt or polyethylene. The polymer system coats each grain and prevents contact between the waste and any surrounding groundwater or surface water. Asphalts and asphalt blends are generally the least expensive materials for waste incorporation. Concentrations of heavy metals measured in EP extracts and distilled water leachates prepared from asphalt microencapsulated electroplating waste are given in Tables 4 and 5.

TABLE 4. RESULTS OF EP TESTING OF TREATED AND UNTREATED TOXIC METAL SLUDGES

Solidification Treatment	As	Cd	Cr	Cu	Hg	Pb	Ni	Se	Zn
Cement-based									
A	<0.01*	<0.0002	0.308	0.153	<0.0002	<0.001	0.006	<0.010	<0.05
B	<0.01	0.0006	0.299	0.150	<0.0002	<0.001	0.005	<0.010	<0.05
Average**	<0.01	0.0004	0.304	0.152	<0.0002	<0.001	0.006	<0.010	<0.05
Pozzolan-based									
A	<0.01	0.0022	0.554	0.104	<0.0002	<0.001	<0.003	<0.010	<0.05
B	<0.01	<0.0002	0.540	0.068	<0.0002	<0.001	<0.003	<0.010	<0.05
Average	<0.01	0.0012	0.547	0.086	<0.0002	<0.001	<0.003	<0.010	<0.05
Asphalt-based									
A	<0.01	<0.0002	<0.001	0.007	<0.0002	<0.001	<0.003	<0.010	<0.05
B	<0.01	<0.0002	<0.001	0.007	<0.0002	<0.001	<0.003	<0.010	<0.05
Average	<0.01	<0.0002	<0.001	0.007	<0.0002	<0.001	<0.003	<0.010	<0.05
Untreated									
A	<0.01	0.643	0.350	2.72	<0.0002	<0.001	0.427	<0.010	2.83
B	<0.01	0.912	0.341	2.50	<0.0002	0.004	0.441	<0.010	3.01
Average	<0.01	0.778	0.346	2.61	<0.0002	0.002	0.434	<0.010	2.92

*All values are in mg/liter.

**Values below the limit of detection were considered to be at the limit of detection in calculating averages when above detection limit results were obtained on the duplicate samples.

TABLE 5. RESULTS OF DISTILLED WATER LEACHING OF TREATED AND UNTREATED ELECTROPLATING WASTE

Solidification Treatment	As	Cd	Cr	Cu	Hg	Pb	Ni	Se	Zn
Cement-based									
A	0.043*	0.0036	2.68	1.18	0.0002	<0.001	0.075	<0.010	<0.050
B	0.043	0.0035	2.86	1.39	0.0005	<0.001	0.077	<0.010	0.104
Average**	0.043	0.0036	2.77	1.28	0.0004	<0.001	0.076	<0.010	0.077
Pozzolan-based									
A	0.033	0.0027	5.67	1.06	<0.0002	<0.001	0.038	<0.010	<0.050
B	0.013	0.0021	6.87	1.06	<0.0002	<0.001	0.052	<0.010	<0.050
Average	0.023	0.0024	6.27	1.06	<0.0002	0.001	0.045	<0.010	<0.050
Asphalt-based									
A	<0.01	<0.0002	<0.001	0.022	0.0002	0.001	<0.001	<0.010	<0.050
B	<0.01	<0.0002	<0.001	0.019	<0.0002	<0.001	0.006	<0.010	<0.050
Average	<0.01	<0.0002	<0.001	0.020	<0.0002	0.001	0.003	<0.010	<0.050
Untreated									
A	0.056	0.063	0.823	0.237	0.0003	<0.001	0.180	<0.010	0.136
B	0.078	0.068	0.921	0.259	0.0003	<0.001	0.193	<0.010	0.129
Average	0.067	0.066	0.872	0.248	0.0003	<0.001	0.186	<0.010	0.132

*All values are in mg/liter.

**Values below the limit of detection were considered to be at the limit of detection in calculating averages when above detection limit results were obtained on the duplicate samples.

Table 6 gives the slurry pH measured for encapsulated and untreated wastes in stirred distilled water. The EP test was run using the standard procedure outlined in the Federal Register (29). The distilled water extraction was prepared by adding 100 ml of crushed (<10 mm diam) sample to 400 ml of distilled water. The sample in water was sealed in a capped bottle and shaken at 140 cycles/min in a reciprocal shaker for 30 minutes. The sample bottle was allowed to settle for 1 hour and the liquid was separated from the solid by filtering through a 0.45-micron membrane filter. The liquid portion was preserved by nitric acid addition to pH 2.0 and analyzed by atomic absorption (heated graphite atomizer technique). The electroplating waste was approximately 20 percent of the weight of the solid. The composition of the waste is given in Table 1 (Sample C).

TABLE 6. SLURRY pH'S MEASURED FOR GROUND AND STIRRED ELECTROPLATING WASTE

Treatment	pH after 2 hours	pH after 72 hours
Cement-based	9.65	9.65
Pozzolan-based	8.45	8.35
Asphalt-based	7.80	7.85
Untreated	8.10	7.75

All of the metals determined in both the EP extract and the distilled water extract were far below the levels of concern. Asphalt microencapsulation appears to be a satisfactory containment system for the electroplating waste tested. The waste used in this testing project was treated to destroy cyanide and to convert hexavalent chromium to trivalent chromium.

In tests where this has not been done, asphalt microencapsulation has been much less successful in immobilizing zinc, copper, and cadmium (20).

Microencapsulation systems using pozzolan-Portland cement and pozzolan cement have been widely used to produce better containment of nuclear, industrial, and military wastes. The general mechanism proposed has involved the mixing of wastes and unhydrated cementitious materials and water. The gelling of the cement encases the particles of waste in a network of silicate fibrils formed during hydration.

Solidifying Portland cement or pozzolanic cement materials produces a mixture of gel, semicrystalline, and crystalline structures, with calcium silicate gel as the major constituent. Other reaction products are crystalline hydrates formed from calcium silicate, calcium aluminates, calcium sulfoaluminates, and calcium sulphoferrites (3, 19). Some of the crystalline calcium silicate hydrate phases have variable composition and can accept magnesium, sodium, potassium, chromium, or manganese in the crystal matrix (18).

Pozzolan-Portland cement- and pozzolan-encapsulated electroplating wastes were examined to determine if any new crystalline phases or changes in the X-ray lattice spacings of standard crystalline phases from hydrated cement (suggesting metal substitutions) could be detected. The two treated wastes used in this study each consisted of approximately 16 percent electroplating wastes (Sample D in Table 2) on a dry weight basis (11).

Traces of the X-ray patterns are shown in Figures 2 and 3. Photos of crushed grain mounts are shown in Figures 4 and 5. No new crystalline phases were observed. Phases typical of carbonated hydrated Portland cement pastes (Table 7) were found in the pozzolan-Portland treated sample, but no changes in lattice spacing that could be attributed to metal substitutions were noted. Similarly in the pozzolan encapsulate, no evidence could be found for involvement of the waste in the crystalline phases that were observed. In both treated wastes, the presence of particles of amorphous metal hydroxides were noted in microscopic examination.

The wastes examined by X-ray diffraction were also subjected to Extraction Procedure (EP) testing and distilled water leaching as described for the asphalt waste. The results of the EP extract analyses and the distilled water leach analyses are presented in Tables 4 and 5. The slurry pH's for the wastes are given in Table 6.

In the EP testing where the waste was in the form of a monolithic cylinder, waste containment was improved for all of the potentially toxic metals examined except for chromium in the pozzolan-based treatment system. Chromium may have been added in the reagents used for solidification.

The chromium and copper levels in the distilled water leachates are higher in leachates from the treated wastes than in the untreated wastes. The reason for this is unknown. The slurry pH's observed with the treated wastes were higher than in the untreated wastes; but in both cases the pH's were closer to the pH's of minimum solubility for these metals as hydroxides (8.5 for chromium and 9.0 for copper) than was the pH for the untreated waste. The slurry pH alone would have suggested that lower, not higher, concentrations of chromium and copper should be observed in the microencapsulated wastes.

A similar problem was noted with silicate polymer-cement treated wastes (21). Water extract of solidified waste with Portland cement and silicate polymer showed higher concentrations of cadmium and chromium than some samples that were similar except no Portland cement was added. The reason for this was not understood.

Radioisotope tracer studies of low concentrations (1.5-2.0 percent of the solid treated wastes) of metal hydroxide sludges encapsulated in concrete (Portland Type I cement) showed an early release of metal ions into a water leach and later resorption (14). The X-ray diffraction work reported in the present study suggests that the resorption process that was noted may be coprecipitation of the heavy metals with calcium as carbonates in calcite or vaterite.

Reactions between carbonate in solution and calcium sulfoaluminates

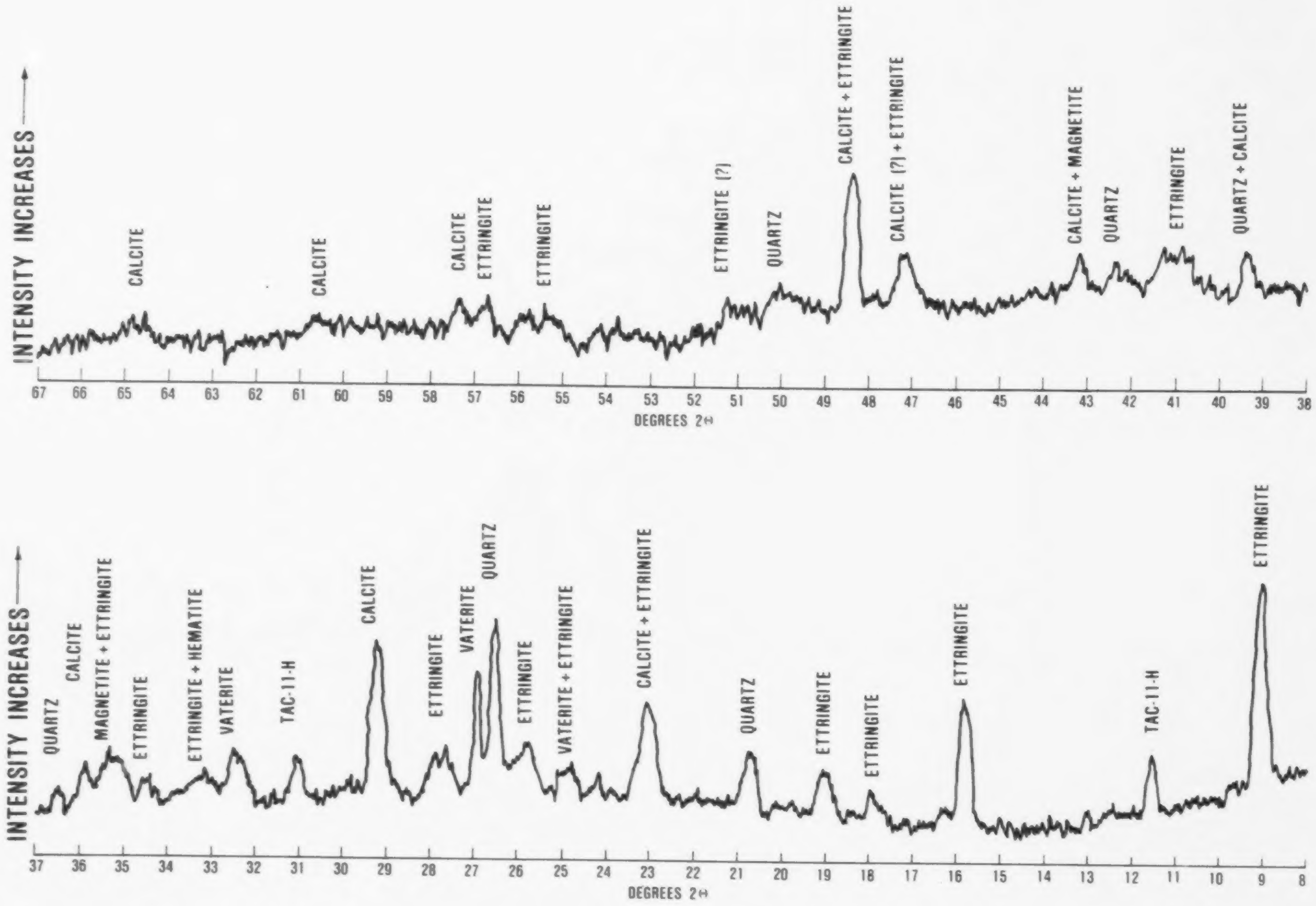

Figure 2. X-ray diffraction pattern from pozzolan-Portland cement-encapsulated electroplating waste.

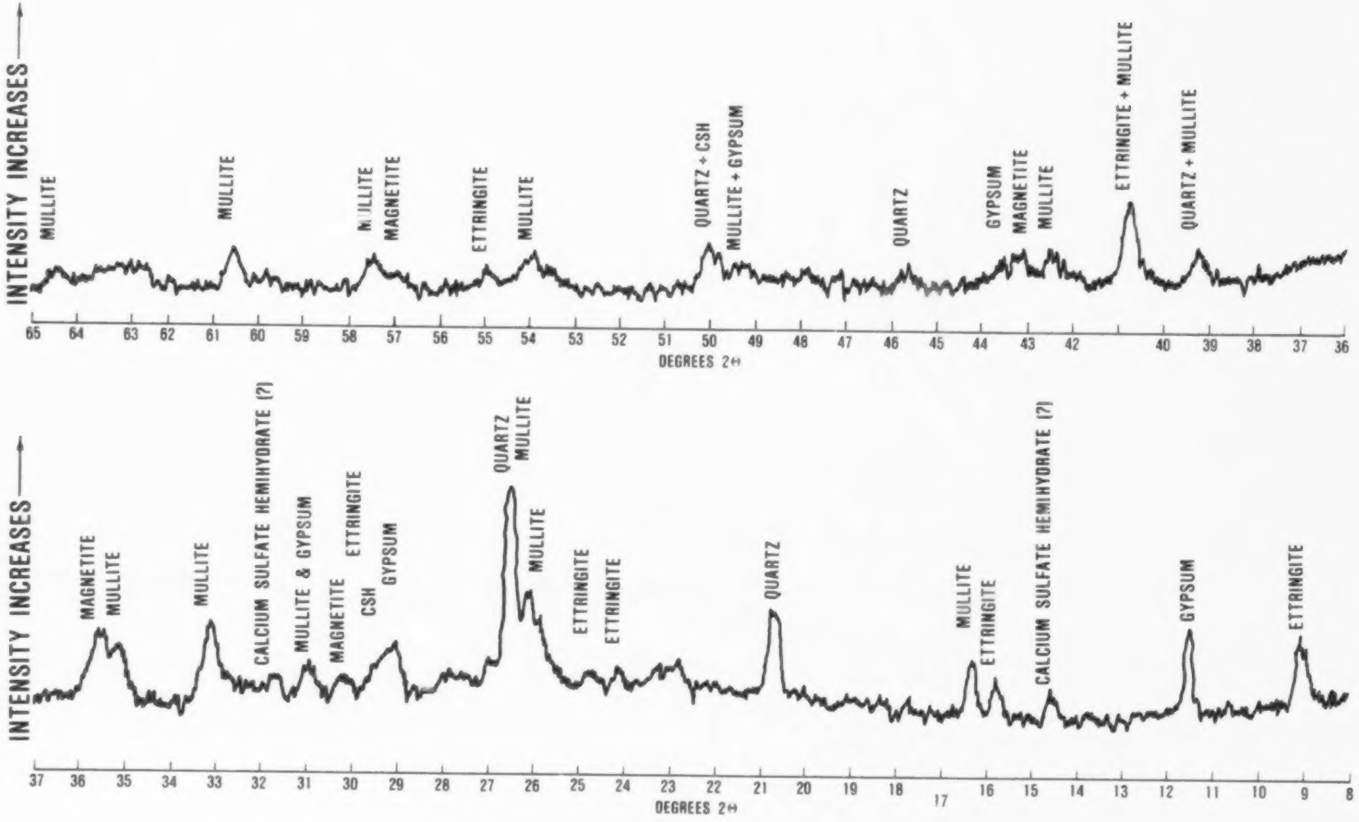

Figure 3. X-ray diffraction pattern from pozzolan-encapsulated electroplating waste.

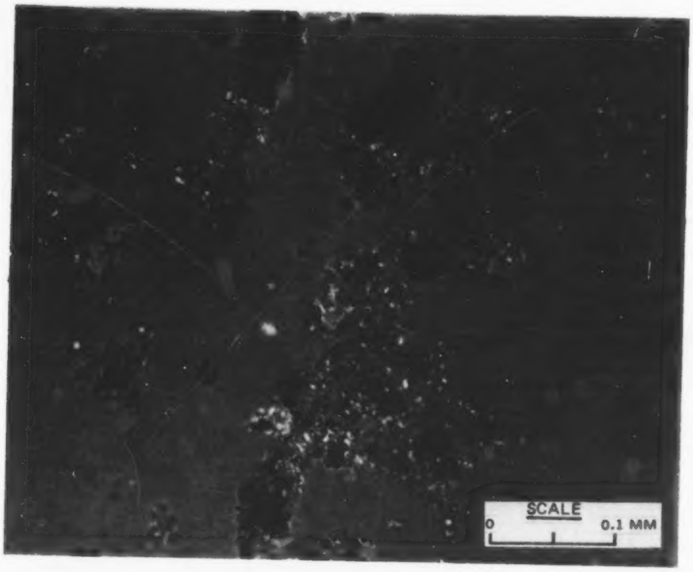

Figure 4. Photomicrograph of crushed pozzolan-Portland cement encapsulated electroplating waste. The spherules are siliceous material from fly ash; the fine transparent crystals are hydrated Portland cement; the large amorphous masses are metal hydroxides. Photo was made with polarized light, under crossed nicols with a gypsum plate.

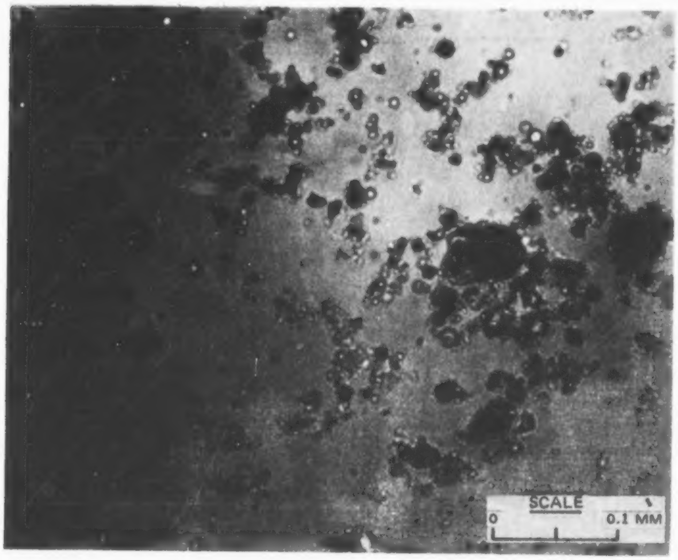

Figure 5. Photomicrograph of crushed pozzolan-encapsulated electroplating waste. The spherules are siliceous material from fly ash; the amorphous masses are metal hydroxides. Photo was made with polarized light, under crossed nicols with a gypsum plate.

TABLE 7. PHASES IN POZZOLAN-PORTLAND CEMENT AND POZZOLAN-TREATED ELECTROPLATING WASTES

Phases Identified	Probable Source
Pozzolan-Portland Cement Treated Waste	
Ettringite	Hydrated Portland cement
Tetracalcium aluminate carbonate-11-hydrate	Hydrated Portland cement
Calcite	Hydrated Portland cement
Vaterite	Hydrated Portland cement
Quartz	Fly ash
Magnetite	Fly ash
Hematite	Fly ash
Pozzolan Treated Wastes	
Calcium silicate hydrate	Reaction of fly ash and lime
Ettringite	Reaction of fly ash and lime
Gypsum	Waste
Calcium sulfate hemihydrate	Fly ash
Mullite	Fly ash
Quartz	Fly ash
Magnetite	Fly ash
Hematite	Fly ash

(ettringite) can cause the precipitation of calcium carbonate. This is a common aging reaction in concrete and causes a gradual increase in the amount of calcite and decrease in the amount of ettringite (2). This type of reaction may account for some of the metal release and reprecipitation observed in waste-Portland cement mixtures. Additional work on Portland cement and pozzolan encapsulates is needed to further understand the interaction of heavy metal hydroxides and gelling cement hydrates. The results reviewed here do not suggest Portland cement is beneficial to waste containment when water leaching is expected.

SUMMARY

Electroplating wastes are a complex mixture of material produced by metal cleaning, etching, and plating. The major persistent contaminants associated with these wastes are potentially toxic metal hydroxides. The amorphous metal hydroxides of cadmium, chromium, copper, lead, nickel, and zinc in these wastes can become significant pollutants if improper disposal techniques are employed.

Several solidification/stabilization techniques have been developed or adapted to assure control of these wastes. New insoluble, non-reactive compounds have been developed for disposal by shallow burial. Systems that are proposed or in use include:

a) Development of silicate mineral analogs that are chemically stable under disposal conditions. The crystalline product must generally be specific for the element to be disposed.

b) Development of low-temperature silicate polymers that can include a variety of potential metal contaminants in a gel-like system. Non-crystalline polymeric materials are, however, generally more leachable than crystalline compounds.

Encapsulates of metal hydroxides have been prepared from a variety of materials.

a) Macroencapsulates produced from polymer-bonded and polyethylene jacketed wastes have shown excellent containment characteristics in testing programs.

b) Microencapsulates produced from organic polymers have been unsatisfactory for electroplating waste when acidification has been used to initiate polymer formation. Better systems that can maintain the wastes as hydroxides have been developed.

c) Thermoplastic microencapsulates have shown excellent containment characteristics for electroplating wastes.

d) Data developed from testing Portland-pozzolan and pozzolan encapsulates indicate that metals in the waste are not involved in the crystal chemistry of the cement or pozzolan setting and hardening process. Analyses of water leachates of crushed wastes indicate the treated waste materials may release more metal than the untreated waste.

ACKNOWLEDGEMENT

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ANALYZING THE COSTS OF REMEDIAL ACTIONS

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Abstract

The Comprehensive Environmental Response, Compensation, and Liability Act of 1980 (Superfund) explicitly requires consideration of cost-effectiveness in the selection of government response actions. Preliminary results from 23 case studies on expenditures of past site responses to uncontrolled hazardous waste sites are presented. These case studies represent a wide range of remedial technologies, response frameworks and response costs. The sites were selected to document information relevant to Superfund responses. The results here include total response costs, an example of a cost section of a case study, and a comparison of costs for excavation, transportation and disposal for 5 sites. Costs for similar technologies appear to vary greatly among the sites due to the particular characteristics of each site. However, understanding the factors that influence costs provides a useful tool for planning cost-effective remedial responses.

INTRODUCTION

In response to growing concern over public health and environmental threats from uncontrolled hazardous waste sites, Congress passed the Comprehensive Environmental Response, Compensation, and Liability Act of 1980, or the so called "Superfund." A major component of implementing Superfund is to conduct remedial actions to prevent or mitigate the long term migration of hazardous substances. Remedial actions are also distinct from other parts of the Superfund, such as removal, in that cost is a concern in formulating the remedial response. In fact, the Act calls for the response to be "cost-effective" although, as the National Contingency Plan points out, concern for cost effectiveness does not take precedence over public health, welfare and the environment. It merely helps to select the least cost alternative from among adequately effective options. For example, cost estimation and cost-effectiveness analysis are key ingredients to the formulation of the feasibility study which underlies the selection, design and implementation of a remedial action. Also, Superfund response action costs must be considered in the fund balancing section of the law. Given the number of Superfund sites it will be expensive to conduct detailed field investigations on all sites to match the reduction in risk and the cost of each site response. A cost estimation model using data on past remedial actions can approximate the required expenditures by extrapolating an estimate from a preliminary description of the site and its problems. The accuracy of the estimate will increase as more information is gathered on each site.

In addition there are two primary needs for cost analysis in managing remedial actions. First, the size of the remedial expenditure will require careful accounting simply from the point of good management practice. As the nation becomes more and more budget conscious, costs of government programs will be subjected to more scrutiny. Superfund, being a high exposure program, will undoubtedly be examined for its financial management. Second, because the state-of-the-art of remedial technology is still evolving quickly, there is also the need to compare expenditures across regions and sites continuously. Contractors will invariably charge costs which contain significant differences reflecting the differentials in the effectiveness of technology and marketing practice. This unstable environment will make the selection of cost-effective remedial actions difficult. A continuously updated documentation of expenditures will significantly increase the management capability of the Superfund program.

This paper presents some of the interim research results of a project carried out by the Environmental Law Institute, in conjunction with JRB Associates, on one aspect of cost analysis, namely the collection and analysis of actual expenditures on past remedial actions. The methodology section will describe site selection, data collection and categorization. Given the fact that the research is ongoing and not all the empirical results are in, this presentation will present a summary of total expenditures by sites, an example of site-specific expenditure analysis and a comparison of off-site disposal costs across the sites.

A few general limitations should be noted at the outset. First, the expenditures were documented on different levels of aggregation, depending on the type of contract and accounting procedures. Results are presented on a comparable level as much as possible, but some accuracy may have been lost in that process. Second, the sites may not be representative of the universe of existing uncontrolled hazardous waste sites, not only of the type of site problems, but also of the cost of the technologies used. Third, hidden costs borne in-house by corporations and government agencies are often not fully accounted for. Finally, market dynamics, such as increasing competition and regulatory requirements have affected response costs over time, which reduces comparability between sites.

METHODOLOGY

Site Selection

The following information sources were used to find potential uncontrolled hazardous waste sites for case study consideration:

- 1981 SCS survey
- EPA Hazardous Material Incidence Reports
- EPA Regional Offices
- State lists of hazardous substance spills and release
- Remedial Action Contractors
- Trade Associations
- Professional Contacts

From these sources, 23 sites were selected using the following criteria:

- Data Availability
- Useful remedial technology
- Post 1975
- Remedial actions completed

Telephone calls and/or letters were used to ascertain the status of the sites and the availability of data. In practice, the availability of data was the most common limiting factor. For this reason, the sites may not be representative of the universe of existing uncontrolled hazardous waste sites and their remedial costs.

Roughly equal numbers of private and government financed remedial actions were chosen, at 12 and 11 sites, respectively. The variety of remedial technologies includes excavation and removal, slurry walls, subsurface drains, solidification and ground water extraction, treatment (carbon, biological and chemical) and reinjection. As of January 1983 the actual draft case study reports have been completed, but the comprehensive analysis section is still being prepared.

Collection of Data

Cost data were generally collected in three stages:

1. Interview preparation
2. Interview and file search
3. Follow-up and refinement.

Before the site visit, readily available cost data were obtained through the mail in preparation for the interviews. Researchers also used available information about work performed at the site to prepare questions and organize the work into useful unit operations and component tasks.

Interviews and file searches during the site visit were the primary sources of cost data. All invoices, memoranda, letters, proposals and contracts were photocopied. This information was usually supplemented by interviews with participating personnel who often recalled numbers that confirmed invoices, helped aggregate related activities, or related dates with activities.

The last phase of data collection was the site visit follow-up. Phone calls and correspondence were used to refine and verify the data. Again, site contacts were helpful in organizing related tasks, and specifying what was or was not included in a contractors' general invoices.

Categorization of Data

The data base resulting from this search consists primarily of three forms:

1. Invoices
2. Reports and correspondence
3. Interviews.

Cost data were constructed into functional categories by two primary means and supplemented with a variety of sources. The categorization method depended on the type of data available from the source. The first method was the aggregation and summing of specific costs on invoices to determine the cost for a general operation such as slurry wall construction. All costs related to a particular task were totalled to derive the cost of the operation. Component costs of the total are described and dissected in the text. Unit costs for items like disposal or slurry mixture were multiplied with the volumes given in as-built engineering reports to double check the numbers.

The second method was the correlation of weekly invoice summaries of general cost categories with the activity occurring during that period to estimate the cost of an operation. Weekly invoice summaries were often categorized by items such as labor, equipment, transportation and disposal. These categories were broken down according to the operation to which its function contributed and the proportion of the weekly total used for that operation. For example, excavation might have been performed for 100% of a given week, and 50% of the labor and 30% of the equipment were devoted to this operation, with the remainder devoted to analytical work. The cost would be further broken down if the daily reports showed that transportation and disposal occurred during two of the seven days included on the invoice for which X % labor and equipment were used for loading and analysis.

These invoice-based methods were supplemented with other sources such as interviews, reports, correspondence and contracts. When aggregating specific invoice items, particular items were sometimes explained by references to file material or the site contacts. The breakdowns of general invoice summaries according to daily reports were often refined by interviewing or corresponding by mail with site contacts about the execution and timetable for particular operations. In-house costs were estimated, when available, by totalling company time sheets for the appropriate project. In-house costs were the most difficult cost to obtain, usually because of the lack of available records.

RESULTS

Of the 23 case study cost sections, 11 were based on invoices or invoice summaries, 6 were based on interviews with corporate officials and engineers, and three were based on reports and correspondence from contractors. One report (Richmond Sanitary Services) was based on estimates using daily progress reports and the 1983 Means Construction Cost Data manual because the ditch construction was performed using non-invoiced in-house resources. The sources for individual cost sections are discussed in the "Project Cost" section each report.

The following three preliminary cost result sections are presented below:

- o Total project costs
- o Specific site involving both capital and operation and maintenance costs for groundwater treatment
- o Comparison of excavation, transportation and disposal costs.

Again, these results are preliminary and are intended here to show the range of observations in the data base rather than provide a comprehensive summary. This limitation is probably especially relevant to the total project cost section.

In specific sites, two general cost categories were observed:

- o Containment/collection/treatment
- o Excavation, transportation & disposal

The containment/collection/treatment costs consisted of several subtasks such as capping, cut-off walls and treatment system construction, as well as operation and maintenance costs for the systems. The "Cost and Funding" section of Anonymous Site X is presented below (Table 1) to show these types of cost elements, which are described in more detail in a separate section of the case study . The costs for excavation, transportation and disposal were often found to be the largest single cost category for the sites involving that response. A chart is used to compare to compare results of this important cost category.

Total Cost by Site

The total cost for each of the 23 sites is shown in Table 2 and the distribution of totals is shown in Figure 1. The average cost per site was about $1.4 million ($1,394,463.10), but the standard deviation of $2.2 million ($2,205,344) shows a wide variation in the costs. The total site costs ranged from $23,000 to $10.3 million. Sixteen of the 23 sites were between $500,000 and $1.5 million.

The variation on the total costs shows not only the variation in the actual site costs, but reflects artifacts in the data base as well. The low end of the total cost range includes a site that involved significant in-house costs that were not accounted for in record keeping, and could not be included in the total. The site at the high end of the range includes significant disposal costs that may be considered part of the work necessary for ongoing facility operation. The inclusion or exclusion of aquifer restoration work significantly affected total costs. Many sites involved only removal of the source of contamination but not the contaminated ground water; and of those sites where ground water restoration projects occurred, a wide variety of levels of effort and success were encountered.

COST AND FUNDING OF ANONYMOUS SITE X

Source of Funding

The owner of Anonymous Site X (Anon X) paid for all project costs. The state did not seek any compensation from the owner for the monitoring costs.

TABLE 1. SUMMARY OF COST INFORMATION ANONYMOUS SITE X

Task	Quantity	Actual Expenditure	Unit Cost	Period of Performance
A. Surface Sealing and Drainage (a)	--	Subtotal: $734.100	--	1981
1. Asphalt paving	135,000 sq.ft. (12542 m^2)	($155,000 (b)	$1.15/sq.ft ($12.36/m^2$)	
2. Betonite cap with gravel	156,000 sq.ft (14,493 m^2)	($177,000 (b)	$1.13/sq.ft. (12.21/m2)	1981
3. Curbs and gutters	4,125 feet (1,265 m)	($132,800)	$32/foot ($105/m)	1981
B. Oil Recovery System (c)		Subtotal: $846,200 ($337,000)	--	1981
1. French Drain (d)	length: 210 ft. (63m) depth: 22.5 ft.(7m)		$1,605/foot ($5,264/m)	1981 1981
2. Operation and Maintenance of Treatment System	1,000-1,500 gallons (3,785-5,678 l/month	$50,000/year	$2.70-4.16/gallon ($0.73-1.10/l)	1982
TOTAL Project Cost	--	$1,580,300	--	1981

(a) Subtotal also includes other costs given in Table 2.

(b) Cost includes half of $42,000 cost for grading.

(c) Subtotal also includes other costs given Table 3.

(d) Excluding sump cost.

TABLE 2. TOTAL COSTS OF SITE RESPONSES

Site Name	Primary Response Technology*	Total Site Cost
1. Anonymous A	Waste water disposal, cut-off wall	$ 10.3 million
2. Anonymous B	Subsurface Drain	$268,217
3. Better Brite	Subsurface Drain	$ 23,000
4. Biocraft	Ground water collection, biodegradation	$926,153
5. Chemical Metals Industries	Removal, disposal, capping	$341,349
6. Chemical Recovery Systems	Cut-off wall, subsurface drain	$1.428 million
7. College Point	Removal, disposal, solidification	$1.75 million
8. Fairchild Republic	Removal, disposal, capping	$450,000
9. Gallup	Removal, disposal, in situ lime treatment, capping	$610,445
10. General Electric	Subsurface, drain, cappin, run-off control	$1.58 million
11. Goose Farm	Removal disposal, Ground water collection, carbon treatment	$5.1 million
12. H & M Drum	Removal, disposal, aeration, capping	$1.246 million
13. Houston Chemical	Removal, disposal, biodegradation	$709,423
14. Howe, Inc.	Removel, disposal, ground water recovery	$470,000
15. Marty's SMC	Removal, disposal, aeration, capping	$419,250
16. N.W. Mautne	Subsurface Drain	$ 79,110
17. Occidental Chemical	Ground water collection, carbon treatment Removal, disposal, capping	$2.66 million
18. Quanta Resources	Removal, disposal, waste water treatment	$2.256 million
19. Richmond Sanitary	Cut-off Wall	$111,036
20. Stroudsburg	Slurry wall, recovery well	$594,500
21. Trammell Crow	Solidification, capping	$427,527
22. Univ. of Idaho	Removal, disposal	$174,897
23. Vertac Chemical	Removal, disposal, Subsurface drain, capping, cut-off wall	$143,000

* See complete description of site responses in ELI/URB Case Studies, 1983.

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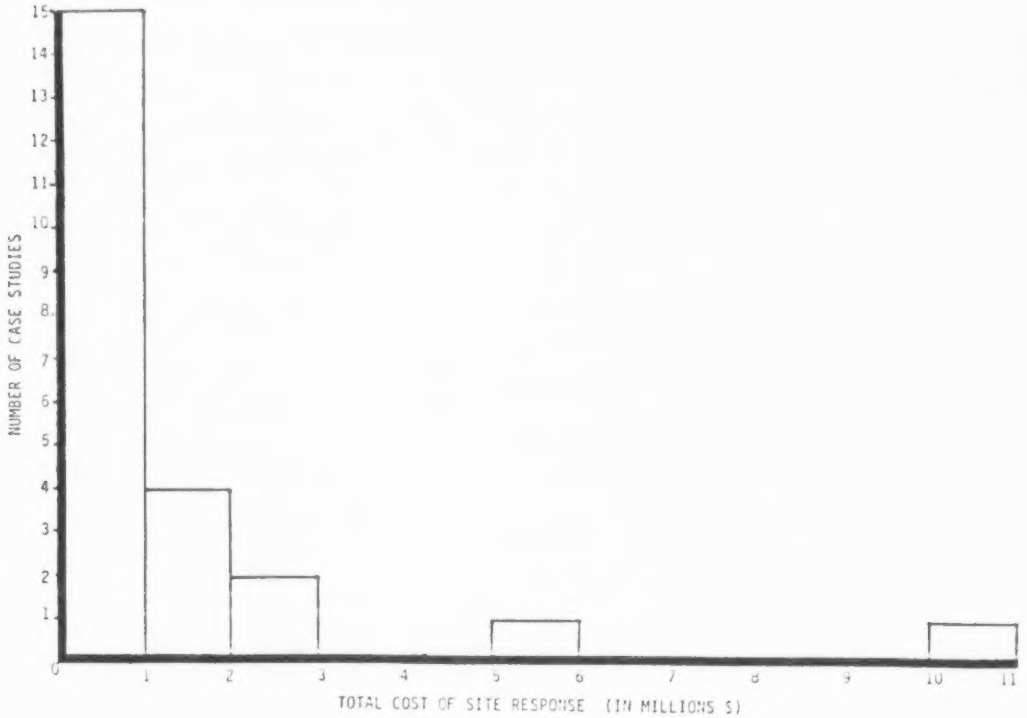
FIGURE 1. DISTRIBUTION OF TOTAL SITE COSTS



Selection of Contract

No information is available on the contractor selection process.

Project Cost

The total construction costs for surface sealing and drainage, and the oil recovery system, was about $1.6 million (see Table 2). This cost does not include preliminary study and design work. No cost information available for this work, which included monitoring well installation, sampling and analysis, and repair, as well as design and planning. The cost information given below is based on interviews with company engineers and on invoices.

SURFACE SEALING AND DRAINAGE

The sum cost of $734,000 for surface sealing and drainage includes the variety of expenditures shown in Table 3. The $43,000 cost of grading is split between asphalt and clay capping costs for the purpose of calculating unit costs. At a cost of $155,000, the unit cost for the 135,000 square feet (12,542 m^2) of asphalt pavement was $1.15/square foot ($12.26/m^2). At a cost of $177,000, the unit cost for the 156,000 square feet (14,493 m^2) of bentonite capping with a gravel cover was $1.13/square foot ($12.21/m^2). The 4,150 feet (1,256 m) of curbs and gutters was determined by dividing the total cost of $132,800 by the unit cost of given of $32/foot ($105/m).

TABLE 3. EXPENDITURES FOR SURFACE SEALING/DRAINAGE

Equipment mobilization	$ 26,000	
Equipment demobilization (including cleaning)	$ 3,600	
Paving	$134,000	
Perimeter fencing	$ 6,000	($10/foot, $33/m)*
Drainage system pipe	$150,000	($18/foot, $59/m)*
Curb and gutter	$132,800	($32/foot, $105/m)*
Manholes	$ 4,700	($280 each)
Monitoring equipment at end of of manhole for surface sealing	$ 12,000	
Supervision (on-site contractor and consultant oversight	$ 20,000	
Soil removal	$ 47,000	($23/yd^3, $30/m^3)
Clay sealing; top rock	$156,000	
Subtotal	**$734,100**	

* Unit costs are as-built

OIL RECOVERY AND TREATMENT SYSTEM

The total of $846,200 for constructing the oil recovery and treatment system includes items shown in Table 4. At a total cost of $337,000 for the French Drain, the unit cost (based on arm lengths of 60,70 and 80 feet (18,21 and 24 m) of constructing a total of 210 feet (63 m) of 20-25 feet (6-8 m) deep trenches was about $1,605/ linear foot ($5,264/m). This cost excludes expenditures for the sump and other related costs.

The total Operation and Maintenance (O. & M.) cost for treating about 1,000-1,500 gallons (3,785 - 5,678 l)/ month excludes equipment amortization and about two hours/ week of the plant manager's time to perform batch treatments. At a total O. & M. cost of about $50,000/year, the unit cost for this initial rate of treatment is $2.70 - 4.16/gallon ($0.73 - 1.10/l).

COMPARISON OF UNIT COSTS

A sample of the unit costs for excavation, transportation and disposal is shown in Table 5. The site characteristics are listed for each site to describe some of the factors that may influence costs. The unique elements of each site are described in the text of each case study.

Since disposal costs were found to depend on the nature and extent of contamination, the waste at each site presented in Table 2 is generally for soil contaminated with non-PCB chlorinated organics. Disposal costs of PCB contaminated soil were typically much higher and are described in the ELI/JRB case studies report. One of the case studies, involved 12 separate disposal costs for the 13 different waste streams identified on-site. These waste streams were segregated according to physical and chemical characteristics, which affected handling characteristics and regulatory requirements for disposal.

TABLE 4. OIL RECOVERY AND TREATMENT SYSTEM ITEMS

Equipment mobilization and and demobilization	$ 65,000
Sump, including sheet piling	$ 85,000
Water treatment system, oil/water separator, pumps and plumbing	$129,200
Tank farm building, plumbing modifications on existing tank farm to receive material before treatment to test for treatment need	$ 58,000
Sanitary sewer system modifications, and monitoring equipment to discharge treated effluent to EBMUD, plus project management	$ 65,000
Electrical and instrumental oil recovery system	$117,000
French Drain System	$337,000
Subtotal	**$846,200**

Excavation, Transportation and Disposal

The average cost for excavation, transportation and disposal for the four sites was $153.82 - 179.02 (standard deviation $72.17 - 87.77). All excavation and transportation costs are at least an order of magnitude higher than the SCS estimates. These differences may reflect the secondary costs associated with these operations such as safety procedures, sampling and inspection. For example, a $5/hour surcharge is typically added to labor costs for using protective gear, and split spoon sampling of each truck load is typically performed. Further discussion of the factors affecting excavation, transportation and disposal costs as well as capital and operation and maintenance costs will be given in the analysis section of the final case study report.

CONCLUSION

The preliminary results on the costs of site responses to uncontrolled hazardous waste sites presented above provide a useful range of actual costs as well as a pratical guide to the variety of realistic cost considerations. The data base's usefulness is both limited and enhanced by the fact that it shows a range of costs across types of sites as well as across the technologies used to respond to the sites. Two general observations can be made on the complexities of analyzing the costs of site responses at uncontrolled hazardous waste sites. The first, and perhaps most important, is that a unique combination of a finite set of factors influences the costs of site responses to varying degrees. When these factors are clearly identified and described, the variance in costs for similar actions can be explained. For the same reason, cost figures, isolated from these factors, are not useful; future cost estimation will have to incorporate these factors in some way. Second, future documentation of remedial action costs should look for consistency and a format that will be useful to decision making in remedial actions. Such improvements can greatly enhance the effectiveness of future remedial actions.

TABLE 5. COMPARISON OF UNIT COSTS FOR EXCAVATION, TRANSPORTATION AND DISPOSAL

Activity	SITES				
	Gallup	Houston, Mo.	Goose Farm, N.J.	Howe, Inc., Minn.	Marty's
Excavation	$14.02/m^3$	$40-$90/m^3$	$ 44-90/m^3$	$10.00/m^3$	
Transportation	$73.96/Mt (800 km)	$26/Mt (273 km)	$63/Mt (708 km)	$37.37/Mt (225 km)	$148.50/Mt (825 km)
Disposal	$44.09/Mt	$48/Mt	$44/Mt	$10-25/Mt	$92/Mt
TOTAL	$132.07/Mt	$114-164/Mt	$151-207/Mt	$57.37-72.37/Mt	$301.50/Mt
Quantity of Material	3,647/Mt	2,015 m^3	3,900 m^3	1,988 m^3	804 m^3 soil 151 drums excavated 470 Mt soil;151 drums disposed
Type of Material	drums/soil	Wet soil	Drums mixed soil, wastes	ice, snow, lime, sandy soil	Soil, drums
Contaminants	solvents, chlorides, heavy metals	PCP	Various	Pesticides	Mixed solvents, paint sludges Still Bottoms, PCB oil
Level of contamination (on-site soil)	cadmium: 22 ug/g magnesium: 61 ug/g				1 ug/g-1,000ug/g
Health Risk	Moderate to low (presently not a drinking water supply)	negligible			ground water
Environmental Risk	Moderate threat to recreational fishing stream	surface water	Ground and surface water	Ground and surface water	fire, explosion
Excavation Depth	1 - 4 m	10 - 15 cm	5 - 8 m	30 - 60 cm	1 - 5 m

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COSTS OF REMEDIAL ACTIONS AT UNCONTROLLED HAZARDOUS WASTE SITES

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ABSTRACT

Subsequent to the passage of the Superfund Act, the U.S. Environmental Protection Agency and other regulatory agencies were faced with the dilemma of selecting cost-effective remedial actions for uncontrolled hazardous waste sites. This paper summarizes two documents being developed to aid regulatory officials in their decision-making process on Superfund site cleanup. The first document outlines the steps to be taken in costing alternative remedial action unit operations, and in combining these unit operations to yield costs for an entire remedial action scenario. Unit operation costs for each of 21 different remedial actions are presented in this paper. Examples are provided of the costing methodology for applying remedial actions at each of landfills and surface impoundments.

This first document, however, relied primarily on information available from standard construction references and past applications not dealing specifically with hazardous waste. This was done since the literature was found lacking back in 1980, and since costs from actual Superfund operations were not yet available. The purpose of this second document is to collect remedial action cost data that has recently become available from site cleanup contractors and regulatory authorities. The emphasis on this second project is to be placed on the incremental costs associated with worker health and safety.

INTRODUCTION

In December 1980, The U.S. Congress passed legislation entitled "The Comprehensive Environmental Response, Compensation, and Liability Act", which is also known as Superfund. Superfund provides the U.S. Environmental Protection Agency (EPA) with the legislative mandate and monetary base to assist in the elimination of public health hazards posed by uncontrolled hazardous waste sites. Section 105 of the Superfund legislation requires the EPA to investigate the costs of remedial/cleanup actions at uncontrolled waste sites. Specifically, Item 2 of Section 105 requires the development of cost ranges for various types of remedial actions.

Responsibility for implementing Superfund actions and responding to uncontrolled hazardous waste sites rests primarily with the EPA Office of Emergency and Remedial Response (OERR). At the request of OERR, the EPA Office of Research and Development (ORD) has performed work on remedial action technologies and costs. SCS Engineers was contracted by ORD to review, update, compile, and integrate existing data on remedial action costs at hazardous waste sites.

This paper provides a review of two SCS projects undertaken to determine remedial action costs. The basic approach taken in developing these costs was to identify the individual remedial action unit operations which can be combined to form an entire remedial action plan, or scenario. Individual unit operations can, in turn, be broken into several cost components which lend themselves to easy costing. By determining the costs associated with these component cost items, the total unit operation cost can be developed. Subsequently, an entire remedial action plan for a site can be costed by summing the costs of the remedial action unit operations.

The first project, "Costs of Remedial Actions at Uncontrolled Hazardous Waste Sites", compiled and classified existing cost data in terms of scope, location, and time frame. A methodology was then provided for computing the costs of remedial action unit operations. The final report was generated in early 1981. The document was intended as a compilation of previous, more general reports generated in prior years. Because of the lack of actual Superfund efforts that had been performed to that time, this report relied primarily on standard construction cost references. In some cases, the costs incurred at similar, commercial applications of such remedial actions (i.e., at other than actual, uncontrolled hazardous waste sites) were utilized.

The costs included in the document above can be described as "base construction costs". Admittedly, they may not sufficiently address the added cost encountered on some unit operations due to the handling of hazardous materials. However, remedial actions are now being implemented at initial Superfund sites. Additionally, numerous contractors desiring to acquire Superfund-related work have purchased the necessary equipment, and performed research on the technologies to be applied and costs to be encountered. Thus, it is thought that more accurate remedial action cost information can now be obtained from these sources. This new cost data should adequately address concerns for worker health and safety, and their impacts on total site costs.

REMEDIAL ACTIONS

A total of 21 remedial action unit operations were identified and costed in the course of the first project. They were derived chiefly from earlier EPA reports on the subject of remedial actions. [1, 2, 3] As shown in Table 1, they have been generally classified into 4 areas: (1) surface water controls, (2) ground water controls, (3) gas migration controls, and (4) waste controls.

Table 1 identifies a total of 6 surface water controls, with 5 applicable to landfills and a slightly different set of 5 applicable to impoundments. Surface water controls are usually considered short-term measures and can be effective in controlling imminent pollution dangers and discharges to surface waterways. Often however, they need to be used in conjunction with ground water controls as described subsequently.

A total of 8 ground water controls are identified in Table 1. These controls are generally considered to be more long-term in nature than are surface water controls. But while curtailing the more long-term environmental impacts such as ground water pollution, they can also be expected to require more sophisticated technologies, longer lead times, and larger funding levels.

TABLE 1. REMEDIAL ACTION UNIT OPERATIONS

Remedial Action Unit Operations	Applicability Landfills	 Impoundments
Surface Water Controls:		
1. Regrading and Surface Water Diversion	●	●
2. Surface Sealing with Asphalt	●	●
3. Revegetation	●	●
4. Cutoff Trenches	●	●
5. Basins and Ponds	●	
6. Containment Berms		●
Ground Water Controls:		
7. Slurry Trench	●	●
8. Grout Curtain	●	●
9. Sheet Piling Cutoff Wall	●	●
10. Grout Bottom Sealing	●	●
11. Underdrains	●	●
12. Well Point System	●	●
13. Deep Well System	●	●
14. Well Injection System	●	●
Gas Migration Controls:		
15. Gas Venting Trench	●	●
16. Gas Extraction Wells	●	●
Waste Controls:		
17. Treatment of Contaminated Water	●	●
18. Chemical Fixation	●	●
19. Chemical Injection	●	●
20. Excavation and Reburial	●	●
21. Leachate Recirculation	●	

Ground water controls can generally be classified into active and passive systems. Slurry trenches, grout curtains, sheet piling walls, grout bottom sealing, and underdrains are all considered passive systems, and operation and maintenance (O&M) requirements are usually low or non-existent. Active systems include well point systems, deep well systems, and well injection systems. In addition to high capital costs, active ground water controls usually require on-going O&M efforts such as electrical service, pump maintenance and replacement, and possibly treatment of contaminated ground water.

Both gas migration controls were found to be applicable to each of landfills and impoundments. Organic materials buried in landfills or closed surface impoundments often generate combustible methane gas. In many cases, combustible gases have been found to migrate laterally from such facilities, posing a risk of explosion or fire in nearby structures.

Gas migration controls can also be either active or passive. Gas venting trenches are passive systems and can be installed by excavating trenches around facility perimeters. Gases migrating laterally from the site are intercepted by these trenches and vented to the atmosphere. Venting trenches are usually limited to where gases are confined within 20 ft of the ground surface. Where greater migrating depths are encountered, active gas migration controls are required. These systems consist of large diameter extraction wells, header pipes, and central blower facilities. Extracted gases are vented or flared to the atmosphere.

A final category of remedial action unit operations is identified as waste controls. While all 5 were found applicable to landfills, only 4 were deemed appropriate for impoundments. Treatment of contaminated water was meant to describe the removal of low level contamination from polluted runoff (as opposed to heavily-contaminated waste materials). Chemical fixation and injection can be effective in stabilizing waste masses and preventing further emission of contaminants. "Excavation and reburial" is usually an expensive proposition; the health and safety hazards affiliated with removal of the hazardous (and often unknown) waste material may exceed the hazards of leaving the waste in-place. Lastly, leachate recirculation can be a temporary measure to treat or dispose of contaminated runoff.

BASE CONSTRUCTION COSTS

Costing Methodology

As mentioned previously, the thrust of this first project was to develop typical costs for remedial action unit operations. In addition, all costs developed were examined for their sensitivity to geographic location and facility type and size. For geographic location, costs for each remedial action unit operation were computed at 3 separate cost levels: "Upper U.S.", "Lower U.S.", and "Newark, NJ". For facility type and size, remedial action costs were examined at 2 types of facilities (i.e., landfills and impoundments), and 5 scales of operation. This paper will concentrate on the third (or medium) scale of operation.

In determining remedial action unit operation costs, each operation first had to be broken down into specific cost components. For example, cost components for bentonite slurry walls were found to include bentonite material, transport, trench excavation, etc. In turn, cost components could be further defined through the use of cost subcomponents, with specific costs assigned to labor, materials, equipment, and supplies.

On this project, assigned costs were in terms of mid-1980 dollars for the U.S. upper and lower city averages in the continental 48 states, as well as for the example location of Newark, NJ. After costs were assigned to each cost subcomponent and thence component, conceptual design cost estimates were accumulated for each remedial action unit operation. Allowances for overhead and contingencies were applied, and total and unit life cycle costs computed.

In most cases, 1980 editions of Means and Dodge construction cost guides [4, 5] were used to obtain the needed costs. Regional adjustment indices presented in the Dodge guide were used to modify the cost estimates for geographical differences. These indices were applied to obtain revised material and labor costs for the "Upper U.S.", "Lower U.S.", and "Newark, NJ", estimates. The indices were not applied to equipment costs since it was assumed that these costs are somewhat constant throughout the nation.

Once all the components within a given unit operation had been costed, the costs were summed giving a subtotal capital cost for each unit operation. As indicated in Table 2, an overhead allowance of 25 percent was then applied to this subtotal, followed by a contingency allowance varying between 10 and 40 percent. The subtotal, capital cost was then added to these overhead and contingency allowances to obtain the unit operations' total capital cost. This method was then applied across all 5 scales of operation.

Efforts then proceeded in costing O&M impacts on the various unit operations. First, an assessment was made as to O&M requirements over an estimated 10-year life cycle. These O&M requirements were then priced in terms of 1980 dollars, inflated to an appropriate value in the year they were to be incurred, and lastly, back-discounted to determine the present value in 1980. Inflation and discount factors are summarized in Table 2. As noted, it was assumed that capital costs were fully incurred in the first year of operation; amortization or financing charges have not been included in this analysis. Also, when work on this project was initiated in 1980, an 11.4 percent discount rate seemed reasonable, and was used. However, it is now likely that Superfund cost estimates will use the 10 percent discount rate recommended recently by the Office of Management and Budget.

TABLE 2. COSTING METHODOLOGY SUMMARY

Capital Costs:		
Base Year	:	Mid-1980
Overhead	:	25%
Contingencies	:	10 - 40%
Terms	:	Fully incurred at time = 0; not amortized
O&M Costs:		
Base Year	:	Mid-1980
Term	:	Annual intervals for 10 years
Future Inflation	:	7.1%*
Discount Rate	:	11.4%

* Except electricity at 9.2%.

Site Profiles

As described previously, site profiles (or hypothetical disposal sites) were developed for landfills and impoundments (i.e., wastewater pits, ponds, and lagoons). Each of these was portrayed at 5 different scales of operation. Only through the use of these site profiles could the individual unit operation cost estimates be computed.

Resulting site profiles were configured to conform to somewhat uniform sets of design criteria and environmental conditions. For both landfills and impoundments, the selected scale of operation was developed in terms of total surface area. This emphasis on surface area is appropriate for uncontrolled waste sites. Daily input volume would be inappropriate since the facilities are no longer active; total storage volume would be inappropriate since the depths of these facilities are often unknown.

Table 3 delineates the operational and environmental conditions developed for the 5 landfill and 5 impoundment profiles. The range of sizes for landfills was developed based on data presented in References [6] and [7]. In addition, it was assumed that the surface area for each landfill was square. Cut slopes were designed at 2:1, with fill slopes at 3:1.

Table 3 also demonstrates the various scales of operation and environmental conditions for impoundment profiles. The range of scale sizes was developed from data in References [8] and [9].

Unit Operation Costs

Selected unit operation costs have been included in this paper as Tables 4, 5, and 6. As indicated, Table 4 provides costs for each of the 21 remedial action unit operations assuming a geographic location of "Lower U.S.", and the medium-scale of operation for each of the example landfill and impoundment. Table 5 assumes a geographic location of "Upper U.S." at medium scales of operation for landfills and impoundments. Table 6 assumes a geographic location of Newark, NJ, also at medium landfill and impoundment sizes.

TABLE 3. SITE PROFILE DATA

Scenario Number	Overall Dimensions Surface Area (ha)	Depth of Waste (m)	Storage Volume (m^3)	Depth from Original Grade To Ground Water (m)	To Waste Volume (m)	To Bedrock (m)
Landfill:						
1	1	11	40,000	4	5	15
2	3	12	200,000	4	5	15
3	5	13	400,000	4	5	15
4	13	14	1,200,000	4	5	15
5	19	15	2,000,000	4	5	15
Impoundment:						
1	0.01	0.5	44	0.5	4	15
2	0.03	1.0	342	1.0	4	15
3	0.32	2.0	6,362	2.0	4	15
4	1.55	4.0	46,575	2.0	4	15
5	9.54	6.0	381,428	2.0	4	15

TABLE 4. REMEDIAL ACTION COSTS - LOWER U.S.

Remedial Action Unit Operation	Unit of Measure	Life Cycle Costs ($/unit) Medium-Size Landfill	Medium-Size Impoundment
Surface Water Controls:			
1. Regrading and Surface Water Diversion	Site area, ha	16,300	35,200
2. Surface Sealing with Asphalt	Site area, ha	67,300	48,402
3. Revegetation	Site area, ha	14,300	3,890
4. Cutoff Trenches	Trench length, m	15	15
5. Basins and Ponds	Site area, ha	647	--
6. Containment Berms	Berm volume, m^3	--	4
Ground Water Controls:			
7. Slurry Trench	Well face area, m^2	61	60
8. Grout Curtain	Wall face area, m^2	937	343
9. Sheet Piling Cutoff Wall	Wall face area, m^2	73	95
10. Grout Bottom Sealing	Site area, ha	5,296,000	1,003,000
11. Underdrains	Pipe length, m	357	1,550
12. Well Point System	Intercept face area, m^2	107	321
13. Deep Well System	Intercept face area, m^2	29	114
14. Well Injection System	Intercept face area, m^2	1,760	109
Gas Migration Controls:			
15. Gas Venting Trench	Site perimeter, m	347	347
16. Gas Extraction Wells	Site perimeter, m	148	148
Waste Controls:			
17. Treatment of Contaminated Water	Flow rate, l/d	3	4
18. Chemical Fixation	Site area, ha	82,500	82,500
19. Chemical Injection	Waste volume, m^3	85	85
20. Excavation and Reburial	Waste volume, m^3	117	389
21. Leachate Recirculation	Site area, ha	19,700	--

As indicated by these tables, unit operation costs are presented in terms of dollars per unit most appropriate for the respective remedial actions. For example, large-scale surface water control techniques such as revegetation and regrading are presented in terms of dollars/hectare. Passive ground water control techniques (or barriers) have been presented in terms of dollars/square meter of wall face in the vertical plane.

Geographic and Size Variations

To demonstrate how individual remedial action unit operation costs have been derived, cost calculations for each of bentonite slurry trenches and well point systems have been included in Tables 7 and 8. Table 7 identifies all the cost components which comprise bentonite slurry trenches. Capital costs include geotechnical investigation, slurry

TABLE 5. REMEDIAL ACTION COSTS - UPPER U.S.

Remedial Action Unit Operation	Unit of Measure	Life Cycle Costs ($/unit) Medium-Size Landfill	Life Cycle Costs ($/unit) Medium-Size Impoundment
Surface Water Controls:			
1. Regrading and Surface Water Diversion	Site area, ha	19,900	52,400
2. Surface Sealing with Asphalt	Site area, ha	92,700	70,705
3. Revegetation	Site area, ha	18,100	5,340
4. Cutoff Trenches	Trench length, m	20	20
5. Basins and Ponds	Site area, ha	1,028	--
6. Containment Berms	Berm volume, m^3	--	6
Ground Water Controls:			
7. Slurry Trench	Wall face area, m^2	103	108
8. Grout Curtain	Wall face area, m^2	1,880	649
9. Sheet Piling Cutoff Wall	Wall face area, m^2	108	135
10. Grout Bottom Sealing	Site area, ha	10,224,000	1,754,000
11. Underdrains	Pipe length, m	416	1,960
12. Well Point System	Intercept face area, m^2	153	398
13. Deep Well System	Intercept face area, m^2	37	149
14. Well Injection System	Intercept face area, m^2	1,785	141
Gas Migration Controls:			
15. Gas Venting Trench	Site perimeter, m	396	396
16. Gas Extraction Wells	Site perimeter, m	268	268
Waste Controls:			
17. Treatment of Contaminated Water	Flow rate, l/d	4	8
18. Chemical Fixation	Site area, ha	145,000	145,000
19. Chemical Injection	Waste volume, m^3	142	142
20. Excavation and Reburial	Waste volume, m^3	120	401
21. Leachate Recirculation	Site area, ha	24,000	--

TABLE 6. REMEDIAL ACTION COSTS - NEWARK, NJ

Remedial Action Operation	Unit of Measure	Life Cycle Costs ($/unit) Medium-Size Landfill	Life Cycle Costs ($/unit) Medium-Size Impoundment
Surface Water Controls:			
1. Regrading and Surface Water Diversion	Site area, ha	19,006	48,700
2. Surface Sealing with Asphalt	Site area, ha	83,610	62,600
3. Revegetation	Site area, ha	17,015	5,000
4. Cutoff Trenches	Trench length, m	19	18
5. Basins and Ponds	Site area, ha	909	--
6. Containment Berms	Berm volume, m^3	--	7
Ground Water Controls:			
7. Slurry Trench	Well face area, m^2	92	94
8. Grout Curtain	Wall face area, m^2	1,643	618
9. Sheet Piling Cutoff Wall	Wall face area, m^2	95	121
10. Grout Bottom Sealing	Site area, ha	8,923,000	1,588,000
11. Underdrains	Pipe length, m	399	1,850
12. Well Point System	Intercept face area, m^2	139	379
13. Deep Well System	Intercept face area, m^2	34	139
14. Well Injection System	Intercept face area, m^2	1,777	132
Gas Migration Controls:			
15. Gas Venting Trench	Site perimeter, m	384	384
16. Gas Extraction Wells	Site perimeter, m	247	247
Waste Controls:			
17. Treatment of Contaminated Water	Flow rate, l/d	4	7
18. Chemical Fixation	Site area, ha	129,500	129,400
19. Chemical Injection	Waste volume, m^3	128	128
20. Excavation and Reburial	Waste volume, m^3	119	266
21. Leachate Recirculation	Site area, ha	22,700	--

TABLE 7. REMEDIAL ACTION COST DERIVATION - SLURRY TRENCH AT MEDIUM-SIZE LANDFILL

	Costs (total*)		
Cost Components	Lower U.S.	Upper U.S.	Newark, NJ
Capital Costs:			
Geotechnical Investigation	$ 3,850	$ 6,520	$ 5,720
Slurry Trench Excavation (10,800 m^3) (720 m x 15 m x 1.0 m)	347,760	588,710	516,670
Bentonite, Delivered (419 tonnes)	27,830	74,200	69,570
Capital Cost Subtotal	$379,440	$ 669,430	$591,960
Overhead Allowance (25 percent)	94,860	167,360	147,990
Contingency Allowance (30 percent)	113,830	200,830	177,590
Total Capital Costs	$588,130	$1,037,620	$917,540
O&M Costs:			
Monitoring			
Sample Collection (12 d/yr, 96 hr/yr)	$ 760	$ 1,570	$ 1,370
Analysis	7,900	7,900	7,900
- Primary & Secondary Parameters			
- 12 background/yr			
- 12 downgradient/yr			
24 samples/yr			
Total O&M Costs	$ 8,660	$ 9,470	$ 9,270
Total Costs:			
Total Life Cycle Cost (over 10 years)	$661,400	$1,117,450	$995,690
Average Life Cycle Cost* (per m^2)	$ 61.22	$ 103.47	$ 92.19

* For a 10,800 m^2 wall face at a medium size landfill (5.41 ha).

TABLE 8. REMEDIAL ACTION COST DERIVATION - WELL POINT SYSTEM AT MEDIUM-SIZE IMPOUNDMENT

	Costs (total*)		
Cost Components	Lower U.S.	Upper U.S.	Newark, NJ
Capital Costs:			
Geotechnical Investigation	$ 9,500	$ 19,500	$ 16,950
Drill Rig Rental (1 day)	280	470	420
Well Points (26 m)	1,040	1,760	1,540
Well Point Fittings (5)	40	70	60
Pump, Centrifugal (1)	1,600	1,600	1,600
Capital Costs Subtotal	$12,460	$ 23,400	$ 20,570
Overhead Allowance (25 percent)	3,120	5,850	5,140
Contingency Allowance (25 percent)	3,120	5,850	5,140
Total Capital Costs	$18,700	$ 35,100	$ 30,850
O&M Costs:			
Monitoring			
Sampling 12 days (96 hr/yr)	$ 760	$ 1,570	$ 1,370
Analysis (24 samples/yr)	7,900	7,900	7,900
Electricity (10,000 kwh)	500	500	500
Total O&M Costs	$ 9,160	$ 9,970	$ 9,770
Total Costs:			
Total Life Cycle Cost (over 10 years)	$96,280	$119,510	$113,580
Average Life Cycle Cost* (per m^2)	$ 321	$ 398	$ 379

* For a 300 m^2 intercept face area at a medium size site (0.468 ha).

trench excavation, acquisition and delivery of bentonite, an overhead allowance, and a contingency allowance. O&M costs are slight and include only sample collection and analysis. O&M costs were assumed to be incurred at face value in the first year, and slightly inflated values for each of the 9 subsequent years. These values are then back-discounted to a present value and added to capital cost to derive total life cycle cost. Unit life cycle costs can then be derived. For slurry trenches, costs ranged between $61 and $103 per square meter of wall face at the medium-size landfill.

Slurry trench economies of scale are demonstrated in Figure 1. As shown, costs do not vary significantly for the 5 scales of landfill operations examined here. In fact, for each of the geographic locations delineated in this figure, costs varied by less than $10 per square meter depending on scale of operation. Conversely, slurry trench construction costs appear to be quite sensitive to geographic location. This was seen as largely a function of proximity to bentonite supplies.

The derivation of unit operation costs for well point systems has been delineated in Table 8. Unlike the previous example for a landfill application, this example applies a well point system to a surface impoundment. Cost components include geotechnical investigation, drill rig rental, installation of well points and fittings, pump installation, and overhead and contingency allowances. O&M considerations include sample collection, analysis, and electricity. Average life cycle costs ranged between $321 and $398 per square meter of intercepted face area.

As shown in Figure 2, differences in scale of operation are shown to be more significant for well point systems than for bentonite slurry walls. While the medium-scale varied between $321 and $398 per square meter, the total variation of this application over all 5 scales of operation is between $100 and $800 per square meter. Considerable savings in large scale operations are mostly due to "once-incurred" costs such as drill rig mobilization, centrifugal pumping facility, and geotechnical investigation.

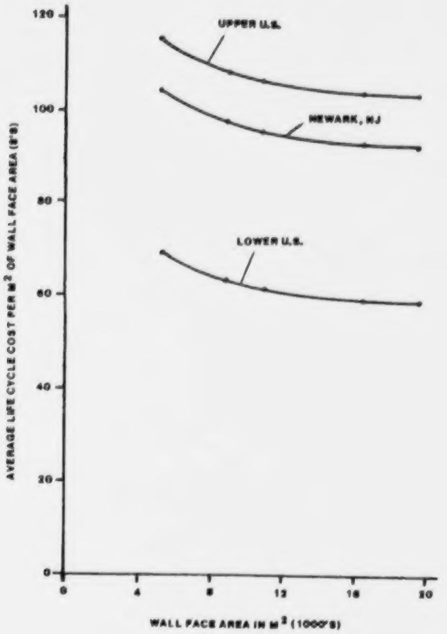

Figure 1. Geographic and Size Variations - Landfill Slurry Trench Costs.

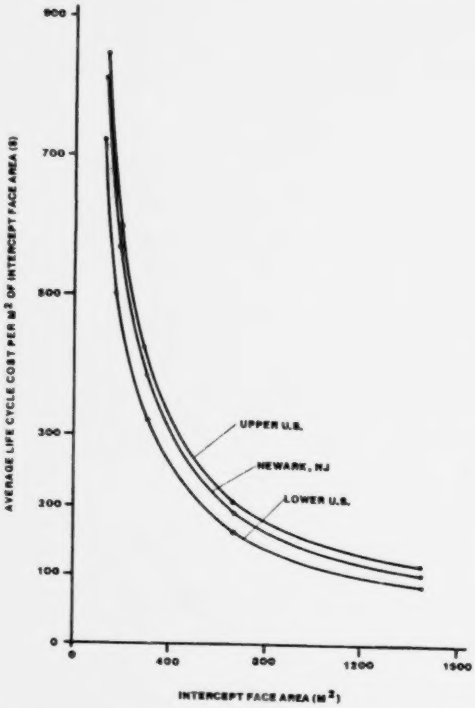

Figure 2. Geographic and Size Variations - Impoundment Well Point System.

INCREMENTAL HEALTH AND SAFETY COSTS

As described previously, outputs of the first project were sometimes found deficient since they do not adequately reflect safety and health impacts on remedial action costs at uncontrolled sites. Rather, costs presented can best be described as "base construction costs" since they were derived chiefly from standard construction cost manuals rather than costs available on applications at uncontrolled hazardous waste sites. Recently however, Superfund activities have proceeded at specific sites and bids for these projects are now available. In addition, various cleanup contractors have prepared themselves for Superfund work. As such, they have developed methodologies for costing cleanup operations and may have specific cost guides to be made available to the authors of this report.

This project was conceived to identify the incremental costs to remedial action unit opeations due to safety and health considerations. These incremental costs are to be limited to worker exposure considerations; health and safety concerns as they may impact on local population are not being taken into account.

As a first step on this new project, a total of 10 health and safety cost items were identified. These were developed from a combination of previous regulatory experience, extensive observations of hazardous waste sites, discussions with contractors, and literature reviews. [10, 11]. Table 9 contains a listing of these 10 health and safety cost considerations. Obviously not all of these considerations are applicable in every case. However, all eventually have an impact within the universe of Superfund activities.

After identifying and defining various health and safety consideration items delineated above, an effort was made to categorize health and safety precautions into several specific groups. Fortunately, the EPA Emergency Response Team has recently developed 4 levels of personal protection as part of its Interim Standard Operating Safety Procedures. [12] These levels of personal protection take into account each of respiratory and skin protection, and are defined in Table 10.

Data Collection Approach

As work proceeded subsequently, contacts were made with hazardous waste site cleanup contractors, regulatory officials, and consulting firms involved in related EPA projects. The information obtained was primarily general cost information on equipment and materials. Specific prices with reference to suppliers and manufacturers were provided for equipment and clothing costs.

Determining the health and safety cost for actual site cleanups proved to be difficult. The number of variables that entered into the various health and safety considerations made comparisons of costs difficult. Additionally, information on costs has traditionally not been collected in a format that enables health and safety costs to be distinquished from other costs. Lastly, information available from bid documents does not provide sufficient detail and/or uniformity to identify and compare specific health and safety cost items.

To resolve these difficulties, hazardous waste site scenarios (i.e., fictional site models) were developed to be representative of 3 basic types of facilities: (1) subsurface burial, (2) surface impoundments, and (3) above-grade storage facilities. Whenever possible these scenarios were developed based on actual cleanup operations either completed, in progress, or planned for the future. This approach was adopted partially to ensure that the scenarios would reflect realistic conditions, and partially to assist in identifying organizations and individuals experienced in particular types of cleanup operations.

Each scenario is composed of a number of distinct unit operations. For each scenario, site characteristics (e.g., topography, size, weather conditions, hydrogeology, etc.) are defined to provide a detailed profile of the site. Similarly, the characteristics of the waste at the site are defined so that the levels of protection can be determined for each unit operation. The levels of personal protection used for the project are those defined by the EPA Emergency Response Team (as delineated earlier).

TABLE 9. HEALTH AND SAFETY COST CONSIDERATIONS

1. Personal Protection:
   - a. Levels of protection
   - b. Types of protection
     - foot
     - hand
     - eyes
     - body
     - head
     - respiratory
     - hearing
     - entry/communications
   - c. Mobile and stationary equipment storage and operation stations
2. Medical Services/Surveillance:
   - a. Medical examinations
     - baseline physical
     - baseline follow-up
     - respirator program
     - unscheduled due to illness or accident
     - follow-up to highly toxic exposures
   - b. On-site
     - first aid (explosions, animal/insect bites, falls, exposures, etc.)
     - emergency communication
     - medical personnel
     - rescue equipment
     - emergency showers/eye washes
     - emergency medical facilities/equipment
     - periodic or continuous monitoring while working
   - c. Off-site
     - transportation (ambulance)
     - medical facilities
     - fire department
     - life squad
     - coordination with health/medical services and authorities
3. Personnel Training:
   - a. Waste handling
   - b. Emergency procedures
   - c. CPR and first aid
   - d. Protective gear/equipment
   - e. Monitoring equipment
   - f. Communication equipment
   - g. Special/seasonal equipment
   - h. Rehearsals
   - i. In-house training
   - j. Outside programs
   - k. Safety and health practices
   - l. Entry and exit procedures
   - m. Technical orientation - basic sciences
4. Manpower Inefficiencies:
   - a. Restricted mobility
   - b. Waste handling procedures
   - c. Monitoring requirements
   - d. Buddy system
   - e. Pre- and post- work activities
   - f. Heat stress
5. Record Keeping:
   - a. Management requirements
   - b. Labor union requirements
   - c. Governmental
   - d. Medical
   - e. Training
   - f. Work history
   - g. Site safety/maps
   - h. Manifests, receipts, and permits
6. Decontamination:
   - a. Personnel
   - b. Protective gear
   - c. Cleanup equipment
   - d. Monitoring equipment
   - e. Required facilities, equipment, structures, etc.
   - f. Change rooms/facilities
7. Site Security:
   - a. Restricting access by personnel or vehicles
   - b. Signs and tags
   - c. Security personnel
   - d. Security systems/equipment
   - e. Coordination with law enforcement agencies
8. Insurance:
   - a. Comprehensive general liability
   - b. Environmental impairment liability
   - c. Workman's compensation
   - d. Specific coverage
   - e. State and federal requirements
9. Emergency Preparedness:
   - a. Fire fighting
     - chemicals
     - extinguishers
     - turnout gear
   - b. Spill containment/control
     - absorbents/chemicals
     - oil booms/containment devices
     - containers and collection equipment
10. Hazard Assessment:
    - a. Sample packaging and shipping requirements
      - special containers
      - special packing materials
      - labels, markings, and placards
      - authorized transporters
      - chain-of-custody
      - manifests and bills of lading
      - waste product information sheets
    - b. Monitoring equipment
      - oxygen detectors
      - combustible gas detectors
      - organic vapor analyzers
      - radiation detectors
      - field test kits
      - specialized laboratory equipment
    - c. Sampling equipment
      - disposable sampling equipment
      - special material construction
      - specialized equipment
    - d. Analytical costs (field and contract laboratories)
      - qualitative
      - quantitative
    - e. Review and interpretation of data
      - establishment of levels of protection
      - source identification
      - assessment of contaminant migration

TABLE 10. LEVELS OF PERSONAL PROTECTION

Level A	Requires full encapsulation and protection from any body contact or other exposure to materials. Toxic by inhalation or skin absorption.
Level B	Requires self-contained breathing apparatus (SCBA). Cutaneous or percutaneous exposure to unprotected areas of the body (i.e., neck and back of head) is within acceptable exposure standards.
Level C	Requires protection for low level concentrations in air. Hazardous constituents may be known. But exposure of unprotected body areas (i.e., head, face, and neck) is not harmful.
Level D	Requires minimal safety equipment. No identified hazards present. But conditions may be monitored and minimal safety equipment made available.

Contractors were identified with particular experience in each type of scenario. Cost information is now being solicited from selected contractors based on their particular experience, availability of qualified personnel, and their willingness to provide the information. Information initially requested is a breakdown of health and safety costs (using the cost component table included previously as Table 9). Costs are to be detailed by these contractors at each of the 4 levels of personal protection, as well as the base construction cost level. This approach was intended to obtain incremental health and safety costs for the specified site, waste, and pollution conditions.

To increase the amount of data obtained from each scenario, further information is being sought on health and safety costs for each unit operation under different waste conditions. For example, if the scenario under consideration includes "excavation and reburial for dioxin wastes with a personal protection Level A" additional costs are also being developed for the same operation involving less hazardous wastes requiring personal protection at each of Levels B, C, and D. A further important refinement is the effect of variable site conditions, particularly weather conditions. Incremental costs associated with extremes of heat and cold are also being investigated as an extension of the scenarios.

The data collected from the scenarios will be used to establish health and safety incremental cost factors for each unit operation identified at each of the 4 protection levels defined in the project. The incremental cost factors will enable adjustment of remedial action construction costs determined using the procedures established in the first project. The adjusted cost estimate will incorporate increased health and safety costs associated with the anticipated hazard conditions on the site in question.

Bid Cost Example

As discussed previously, some difficulty has been encountered in extracting data useful for this project from existing Superfund site bid documents. For example, the format for bid documents on two Superfund site cleanups (designated herein as Sites A and B) contain different levels of detail for bid items to be costed. For Site A, 15 bid items were listed. For Site B, a total of 62 bid items were listed. Table 11 contains the bid quote submitted for Site A. Table 12 contains selected bid items (containing some of the health and safety costs) and the total project cost estimate for 3 of the bids submitted on Site B.

Obviously, tremendous variation is seen in the line items submitted from various firms. For example, bids for insurance, bonds, and permits shown for Site A in Table 11, show a range from about $1,500 and $60,000. Obviously, there are differences in interpretations as to the requirements of insurance, bonds, and permits. In addition, it is entirely possible that some contractors are allocating these costs at least in part to other bid items. Despite the variations noted above, it is interesting to note the relative uniformity of bottom-line costs. Although individual line items may vary by as much as an order of magnitude, the 11 bids received varied within a tighter range of about $880,000 to $1,800,000.

Preliminary Cost Data

From data collected to date, some preliminary cost estimates have been developed. Table 13 is a compilation of the estimated personal protection equipment cost at the 4 levels of hazard. Costs are shown to range from a high of about $1,800 for Level A protection, to a low of only $260 for Level D protection. In

TABLE 11. BID LINE ITEMS FOR SUPERFUND SITE A

Bids	1 Insurance Bonds, Permits	2 Other Project Start-Up and Site Services	3 Site Preparation	4 Liquid Material Disposal*	5 Solid Material Disposal+	6 Salvage of Motors	7 Salvage of Scrap Steel	8 Disposal of Drummed Material Currently on Site	Total
A	$18,143	$ 193,762	$161,680	$135,927	$ 534,640	($ 2,327)	$ 9,400	$ 1,080	$1,052,305
B	$13,625	$ 236,628	$ 80,310	$493,072	$ 423,392	($ 4,310)	($ 4,000)	$ 1,045	$1,239,762
C	$21,500	$1,048,679	$ 34,958	$165,590	$ 536,683	($ 3,590)	($ 5,000)	$ 1,179	$1,799,999
D	$16,000	$ 600,000	$345,835	$199,312	$ 522,760	($ 431)	($ 200)	$ 1,440	$1,684,716
E	$19,000	$ 552,000	$290,000	$266,812	$ 532,000	($ 4,310)	($ 2,000)	$ 4,200	$1,657,702
F	$ 1,500	$ 446,300	$ 60,000	$154,677	$ 659,334	($ 8,620)	($ 4,000)	$ 720	$1,309,911
G	$26,420	$ 190,000	$130,000	$173,250	$1,280,200	($ 4,310)	($ 3,000)	$ 1,680	$1,794,240
H	$20,000	$ 992,248	$296,500	$ 33,025	$ 161,950	($ 1,077)	($ 2,000)	$ 4,200	$1,511,000
I	$11,250	$ 475,581	$187,431	$203,960	$ 297,522	($ 8,620)	($ 2,000)	$ 1,308	$1,166,432
J	$10,000	$ 101,600	$112,100	$211,272	$ 442,340	$ 2,004	$ 2,000	$ 900	$ 882,216
K	$60,000	$ 185,000	$207,753	$336,247	$ 241,000	($43,100)	($ 4,000)	$ 4,500	$ 987,400
Average	$19,767	$ 456,527	$173,324	$215,740	$ 511,984	($ 6,958)	($ 982)	$ 2,024	$1,371,426

* Summation of five bid items.

+ Summation of four bid items.

TABLE 12. SELECTED BID LINE ITEMS FOR SUPERFUND SITE B

Item	Estimated Quantity/ Unit	Bid #1		Bid #2		Bid #3	
		Unit Price	Amount	Unit Price	Amount	Unit Price	Amount
Insurance, Bonds, and Permits	1/L.S.	$ 27,760	$ 27,760	$ 60,000	$ 60,000	$ 39,925	$ 39,925
Medical Examinations	35/person	$ 400	$ 14,000	$ 3,300	$115,500	$ 476	$ 16,674
Security and Communications Center	1/L.S.	$ 5,670	$ 5,670	$ 11,987	$ 11,987	$ 12,285	$ 12,285
Laboratory	1/L.S.	$ 54,139	$ 54,139	$ 34,650	$ 34,650	$ 36,768	$ 36,768
Emergency Medical Facility	1/L.S.	$ 5,611	$ 5,611	$ 8,952	$ 8,952	$ 7,155	$ 7,155
Personal Hygiene Facility	1/L.S.	$ 24,203	$ 24,203	$ 53,575	$ 53,575	$ 37,928	$ 37,928
Equipment Storage Area	1/L.S.	$ 6,812	$ 6,812	$ 4,029	$ 4,029	$ 1,748	$ 1,748
Safety Officer	100/mandays	$ 206	$ 20,600	$ 240	$ 24,000	$ 300	$ 30,000
Custodian	100/mandays	$ 206	$ 20,600	$ 132	$ 13,200	$ 194	$ 19,400
Security Officer, 8 hr Normal Working Day	100/mandays	$ 129	$ 12,900	$ 8	$ 800	$ 80	$ 8,000
Personal Safety Equipment and Protective Clothing	35/person	$ 1,067	$ 37,345	$ 2,000	$ 70,000	$ 2,475	$ 86,625
Preliminary Staging and Sampling Area	1/L.S.	$ 19,471	$ 19,471	$ 9,537	$ 9,537	$ 9,368	$ 9,368
Loading and Waste Consolidation Area	1/L.S.	$121,109	$121,109	$ 54,314	$ 54,314	$ 28,509	$ 28,509
Repack Drums	700/ea	$ 45	$ 31,605	$ 20	$ 14,000	$ 25	$ 17,500
Overpack Drums	700/ea	$ 63	$ 44,065	$ 65	$ 45,500	$ 90	$ 63,000
Equipment Decontamination Facility with Clarifier Unit	1/L.S.	$ 74,223	$ 74,223	$ 35,163	$ 35,163	$ 40,000	$ 40,000
7 ft High Chain Link Fence	1,200/ft	$ 22	$ 26,904	$ 17	$ 70,700	$ 15	$ 18,588
22 ft Wide Double Leaf, Vehicle Chain Link Gate	3/ea	$ 959	$ 2,880	$ 1,037	$ 3,110	$ 545	$ 1,635
Collection and Handling of Washwater	250/drum	$ 83	$ 20,762	$ 188	$ 46,893	$ 88	$ 21,992
Total Project Bid*			$1,492,186		$1,661,079		$1,717,008

* Total includes 43 other line items not directly related to health and safety considerations, and not shown here.

TABLE 13. PRELIMINARY COSTS -
PERSONAL PROTECTION EQUIPMENT

Level A Cost = $1,854

- Fully-encapsulating, chemical-resistant suit
- Pressure-demand, self-contained breathing apparatus
- Gloves, inner, chemical-resistant
- Gloves, outer, chemical-resistant
- Boots, inner, chemical-resistant, steel toe and shank
- Boots, outer, chemical-resistant, disposable
- Hard hat

Level B Cost = $1,136

- Chemical-resistant clothing - jacket, bib overalls
- Pressure demand, self-contained breathing apparatus
- Gloves, inner, chemical-resistant
- Gloves, outer, chemical-resistant
- Boots, chemical-resistant, leggin
- Boots, inner, chemical-resistant, steel toe and shank
- Boots, outer, chemical-resistant, disposable
- Hard hat

Level C Cost = $736

- Sarn-coated disposable suit
- Full-face air-purifying cannister respirator
  - -- front belt mounted
  - -- back belt mounted
- Gloves, inner, chemical-resistant
- Gloves, outer, chemical-resistant
- Boots, chemical-resistant, leggin
- Boots, chemical-resistant, steel toe and shank
- Boots, outer, chemical-resistant, disposable
- Escape mask
- Hard hat

Level D Cost = $260

- Disposable coveralls
- Gloves, outer, chemical-resistant
- Boots, chemical-resistant, steel toe and shank
- Escape mask
- Hard hat and face shield

TABLE 14. PRELIMINARY COSTS -
OTHER HEALTH AND SAFETY ITEMS

Items	Costs
1. Baseline Physical	$150/person
2. Medical Coverage	3 to 10% of base pay
3. Personal Protection (includes clothing and monitoring equipment)	$4,100 to $5,000/person
4. Decontamination (capital)	$12,000 to $15,000/site
5. Decontamination (operational and disposal)	$100/day
6. Site Security (general)	1 to 5% of bid price
7. Site Security (guard service)	$10/hour
8. Training - new employee	5 to 10% of man-hour
9. Training - after 6 months	1 to 5% of man-hour
10. Record Keeping	1 to 5% of working hours
11. Manpower Inefficiencies - losses (primarily affected by temperature extremes and level of protection)	25 to 40%
12. Insurance - Liability	$1 to $2/$100 of sales
13. Insurance - Workman's Compensation	$1 to $25/$100 of wages
14. Insurance - Bonding	20 to 100% of bid price

some respects, protection stipulated for Level D may not differ substantially from typical protective gear applied at normal construction sites.

Other preliminary costs for miscellaneous health and safety items have been included in Table 14. These numbers were compiled based upon extensive interviews with cleanup contractors and other officials and consultants knowledgeable in the field.

CONCLUSION

In current decision-making processes, concern for cost-effective use of funds is a major issue in political, economic, and budgetary considerations. The limitation of available Superfund money to address the problems associated with uncontrolled hazardous waste sites necessitates cost-effective evaluation and selection of remedial actions. This need has been reflected in the requirements of the Superfund Act to provide methods for an analysis of the relative costs of alternative remedial actions. The studies discussed in this paper were designed to assist in fulfilling these requirements.

The primary result of these studies will be a costing methodology which can be consistently applied to the various unit operations and reflect variations due to geographic location, facility size, facility type, and level of personal protection taken to accommodate health and safety concerns. The resulting cost estimates will enable regulatory officials, consultants, and contractors to (1) compare costs for alternative unit operations performing the same function, and (2) budget costs for combinations of unit operations comprising complete remedial action plans. Other useful applications could include:

- Design of a specific unit operation. For example, cost data generated by this project could help determine the location of a bentonite slurry wall. Should it be placed on-site where excavation could require installation at Level C personal protection? Or would it be more cost-effective to move further downgradient where a longer wall would be required to contain the dispersed plume, but personal protection would not be required?

- More study vs start of cleanup actions. For example, should remedial actions proceed immediately without the benefit of detailed waste analyses, assuming that "worst-case" Level A protection is required? Or should further sampling and analyses be performed if there is a possibility that results will allow a lessening of personal protection to Levels B or C?

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DEVELOPMENT OF A FRAMEWORK FOR EVALUATING COST-EFFECTIVENESS OF REMEDIAL ACTIONS AT UNCONTROLLED HAZARDOUS WASTE SITES

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1.0 INTRODUCTION

Background

Many uncontrolled hazardous waste sites across the nation are currently being "cleaned up" or are slated for remedial action implementation in the near future. Part of these remedial actions are being funded by the parties responsible for the site, part by state governments, and others by the federal government under the Comprehensive Environmental Response, Compensation and Liability Act (CERCLA). In any remedial action plan at hazardous waste sites, potential remedial alternatives must be identified and the most appropriate one selected.

The formality required in this identification/selection phase may depend on the source of funding for the remedial action. CERCLA requires that remedial action conducted with Superfund monies be demonstrated to be the most cost-effective alternative that adequately protects human health and the environment. Whether or not state agencies or private contractors use a cost-effectiveness assessment *per se*, some methodology is necessary for selecting the most appropriate plan from a list of potential alternatives.

The Problem

Systematic assessment of remedial action alternatives for uncontrolled hazardous waste sites presents several unique challenges. The most significant of these challenges is the absence of a uniform, well-defined clean-up objective to which the remedial alternatives can be compared on a consistent basis. In the National Contingency Plan (NCP), EPA defines the cost-effective alternatives as "the lowest cost alternative that is technologically feasible and reliable and which effectively mitigates and minimizes damage to and provides adequate protection of public health, welfare, or the environment." Although this guidance mandates consideration of alternatives on a case-by-case basis, it does little to pinpoint what will be considered an acceptable level of cleanup.

Remedial alternatives may also show wide variances in timeframes over which they are effective; in many cases, this timeframe is unknown. Cost-effectiveness evaluation of remedial alternatives must incorporate and effectively address a number of factors which are subjective, difficult to quantify and for which a common metric, such as dollars, cannot be established.

Radian Corporation, under contract to EPA's Municipal Environmental Research Laboratory in Cincinnati, Ohio, is developing a methodology for assessing cost-effectiveness of remedial action alternatives. The project, initiated in June 1982, will be completed in 1983.

Objectives and Criteria

The basic objective in developing a methodology for assessing cost effectiveness is to provide for consistency in decision-making. The methodology should be simple to apply, requiring only minimal instructions for its use. In this regard, the analysis should be based on the smallest possible number of independent variables that address relevant concerns.

The methodology should not require vast information concerning either site conditions or the remedial alternatives being considered; however, the method should allow for consideration of newly obtained information as it becomes available. Also, the methodology should be conducted with a precision that is consistent with the degree of knowledge about the problem or expected results. Finally, the methodology should incorporate a means for determining the sensitivity of the analysis to judgements made in applying it.

Organization of Paper

This paper addresses the methodology developed for assessing cost effectiveness of remedial action options at Superfund sites. It should be kept in mind that the paper presents the generic framework for assessing cost-effectiveness of remedial actions. This framework must be tailored to address site specific conditions.

The paper introduces alternative methods of evaluating cost effectiveness followed by a step-wise description of the methodology chosen. The primary emphasis of the paper is on the technical aspects of an evaluation matrix and the procedure for using it.

2.0 RELATED APPROACHES

Risk assessment, cost/benefit analysis, cost-effectiveness analysis, and trade-off matrices are types of alternatives evaluation which have been used in assessment of environmental controls. Certain aspects of these evaluation techniques are applicable to cost-effectiveness assessments of remedial action plans.

Risk assessments can be used to determine which options reduce risk to an acceptable level; however, extensive and detailed information is needed. It would be necessary to define the highest acceptable risk which is likely to be very controversial. Cost/benefit analysis could be used to quantify for each option the costs and benefits. If a common standard of measuring benefits could be developed, the lowest cost option could be considered the most cost-effective. Classic cost-effectiveness evaluation (as defined in 40 CFR, September 4, 1973) could be used to compare benefits of competing options but the procedure does not readily conform to a simple analytical format. As is the case with cost/benefit evaluation, comparing options that have different impacts (such as containment versus cleanup) is very difficult. The tradeoff matrix approach rates options against each other in terms of cost and effectiveness. The procedure requires a team of experts to provide the ratings.

3.0 METHODOLOGY DESCRIPTION

A form of trade-off matrix is presented here as the selected methodology for evaluating remedial actions for hazardous waste sites. In this methodology, various alternatives are rated against each other according to various measures of effectiveness or cost. Weighting factors are applied to the individual measures, the measures are rated for each alternative, and a final score calculated for each alternative. An example of the cost-effectivenss matrix is given in Figure 1.

The matrix is to be completed by a team of experts and used in conjunction with a sensitivity analysis. The matrix requires little "reeducation" of the evaluator because it requires only that various alternatives be rated according to the evaluator's knowledge of the situation. It is as usable for situations in which few data are available as for those in which extensive background data exist. In fact, it can be used at more than one point in the project to update assessments as more data become available. Sensitivity of the ranking of alternatives to changes in ratings can easily be measured.

The Evaluation Team

The application of a trade-off matrix requires an evaluation team with expert knowledge of the remedial actions being considered, the present impacts of the site, potential impacts from the site or the remedial actions, and the affected community.

For most sites, an appropriate team would include a ground-water hydrologist or hydrogeologist, an engineer trained and experienced in remedial actions (most often a civil engineer), a health impacts specialist or chemist knowledgeable of the substances involved and their health effects, a surface water hydrologist, and a community impacts specialist, usually a geographer or sociologist.

	Cost Measures				Site Independent Effectiveness Measures								Site-Specific Effectiveness Measures					
Alternatives	Construction	Operation & Maintenance	Other	Σ Cost Ratings	Level of Cleanup/ Isolation Achievable	Time to Achieve Clean-up/Isolation	Technology Status	Usability of Land After Action	Capability of Action to Minimize Community Impacts During Implementation	Capability of Action to Minimize Adverse Health & Environmental Impacts During Implementation	Risk of Failure						Σ Effectiveness Ratings	Σ Effectiveness Ratings / Σ Cost Ratings
Weighting Factors																		
Encompassing Slurry Wall with Cap																		
Downgradient Slurry Wall with Extraction Wells, Treat with Carbon																		
Extraction Wells, Treat with Carbon																		
Extraction Wells, Treat with Bios																		

FIGURE 1

Initial Screening

In most remedial action plans, several technologies are combined into an overall remedial action. The Cost-Effectiveness Methodology can be used to identify a few highly cost-effective alternatives. However, as an initial step the user should screen the list of candidates to eliminate obviously or marginally inappropriate alternatives.

To reduce the number of alternatives to a workable number, the user is to consider the factors presented in the National Contingency Plan. These factors are:

- cost,
- environmental effects during implementation,
- protection of public health, welfare and the environment, and
- feasibility and reliability of the alternative.

Any alternative whose costs far exceed (e.g., by an order of magnitude) the cost of other alternatives is to be excluded. Any alternative that would cause significant adverse impacts during implementation, or that after being implemented would not protect the public health, welfare, and environment is also to be excluded, as is any alternative that is not feasible for the site-specific conditions.

4.0 INPUT TO THE COST-EFFECTIVENESS MATRIX

As a first step, the matrix itself must be constructed (with site-independent and site-specific effectiveness measures and weighting factors) and cost data for the alternatives compiled.

Information Needs

The evaluation team must be familiar with the available information on the site. The types and amount of data available will vary widely from site to site, depending on the amount of previous study of the site. However, any site-specific or regional data that can be used in assessing the feasibility, impacts, effectiveness, risks, and cost of remedial action should be collected, specifically information about environmental conditions, waste information, nature and degree of risk, public issues, and institutional factors.

Site-Independent Effectiveness Measures

The standards against which the various alternatives are to be rated are called "effectiveness measures." Site-independent effectiveness measures are those which apply to almost all remedial action situations. These measures include the following:

- How clean will the site be after the remedial action plan is implemented?
- How long will clean-up take?
- How well will the remedial action reduce health and environmental impacts?
- What are the impacts of performing the remedial action?

- What can the site be used for after clean-up?
- Is this technology proven and feasible?
- What is the risk of failure?
- What would be the impacts of failure?

Site-Specific Effectiveness Measures

For most sites, use of only the site-independent measures will allow a suitable effectiveness analysis. However, in certain cases, conditions or clean-up objectives unique to the specific site may dictate factors considered significant enough to be used as distinct effectiveness measures. These measures are to be as independent of the site-independent and other site-specific measures as possible. Site- specific measures can be used in addition to the site-independent measures or in place of one or more of them.

For example, if a lake downstream of an abandoned site has been contaminated by seepage from the site and if an objective of the remedial action is to restore the usefulness of the lake, the degree to which the remedial action alternatives meet this objective may be added as a measure of effectiveness.

Cost

The cost estimates must account for remedial action construction costs and annual operation and maintenance cost, since these types of costs are specifically identified in CERCLA. A procedure for estimating costs can be found in the EPA report: A Standard Procedure For Cost Analysis of Pollution Control Operations, Volumes I and II, EPA-600/8-79-018a and b.

Social Costs

In addition to the direct monetary costs there are social costs associated with a remedial action at a hazardous waste site.

Though the public may regard the action as beneficial to society, it should be anticipated that some people, organizations, or units of government will perceive some aspects of the remedial action as affecting them negatively. These negative impacts, "social costs," can be either monetary or nonmonetary (psychological).

Social costs are very difficult to factor into any methodology used in selecting a remedial action because they are difficult to calculate and vary widely by site-specific considerations. However, these costs do exist and must be considered.

Five categories of social impacts have been identified as a starting point for this evaluation. These categories are ise useful constructs when looking at the social costs of remedial action. They are:

- psychological impacts,
- sociological impacts,
- political impacts,
- legal impacts; and
- organizational impacts.

Weighting Factors

Weighting factors were identified in the description of the matrix as a way to assign relevant importance to the several cost and effectiveness measures discussed previously. Because the values of weighting factors can change the results of the cost-effectiveness comparison of alternatives as drastically as can any other input, the parties-at-interest in the clean-up should agree on their values. These weighting factors typically range from 0.1 to 1.0 and are multiplied by the ratings that each alternative has been assigned relative to each measure of effectiveness. In this way a high weighting factor, appropriate for a measure considered very important, increases the effect of that particular measures rating on the final outcome. Conversely, low weighting factors are appropriate for less important measures.

5.0 EVALUATION PROCEDURE

There are fifteen distinct steps involved in conducting the cost-effectiveness assessment using the method outlined above. These steps are:

Step 1. Compile background data on the site.

This information should include descriptions of the types and volumes of waste disposed, geologic aspects of the site (e.g., depth to groundwater, soil types, lithology and depth to to confining stratum), and any other data that may exist.

Step 2. Identify appropriate remedial actions.

Based on the outputs of Step 1, viable remedial action alternatives are identified. There is a possibility that some or most of these alternatives will have been defined before the evaluator becomes involved in the assessment process.

Step 3. Identify effectiveness and cost measures.
The measures against which the various alternatives will be assessed are selected by the evaluator. The generic measures, because of their nature, will probably be identified for the evaluator. The site-specific measures will depend on the site characteristics, waste type, surrounding environment, and alternatives being considered. The cost measures will typically consist of construction and operation and maintenance costs, but under some circumstances other cost measures may be included.

Step 4. Assign weighting factors.
The relative significance of all the measures of cost and effectiveness is established, typically by a consensus of the evaluators through a Delphi process. Appropriate weighting factors are then assigned to the measures to reflect their importance.

Step 5. Rate alternatives.
Each alternative is rated (e.g., 1 to 5) relative to its ability to satisfy each measure of effectiveness. The evaluators will depend primarily on their expertise and knowledge of the situation to make appropriate judgements. Additional technical information may be provided to the evaluation team prior to the rating exercise.

Step 6. Examine ratings for "outliers".
Examine the inputs from the evaluation team to identify any individual ratings that seem grossly inappropriate or indicate a potential misunderstanding or extreme insightfulness by an individual evaluator. If such ratings are identified, consult the supplier of each rating to establish why that input was provided. Do not change any rating unless the supplier agrees that the rating was inappropriate and supplies a substitute. If the rating is appropriate, share the information that led the supplier to use that rating with the other evaluators and give them opportunity to change their ratings.

Step 7. Calculate final ratings.
The final rating for each measure of effectiveness for each alternative is then calculated by multiplying the ratings by the appropriate weighting factor. This step enables the evaluator to factor the relative importance of the various measures of effectiveness into the analysis.

Step 8. Sum the final ratings for each alternative.
The sum of all the effectiveness ratings for each alternative is calculated. This step involves summing all the final ratings in a row, each row corresponding to a different alternative.

Step 9. Calculate average of all ratings sums.
Calculate the average effectiveness rating sum for each alternative.

Step 10. Estimate costs.
The costs for construction, operation and maintenance, and any other identifiable costs, are estimated. These estimates may be developed independently by the evaluator or they may be derived from available engineering studies or standard references.

Step 11. Calculate cost ratings.
Cost ratings are calculated by expressing the cost estimates in millions of dollars (e.g., a cost estimate of $753,000 has a corresponding cost rating of 0.753). Appropriate weighting factors may be applied as required. Ratings for each cost measure (e.g., construction, and operation and and maintenance) should be calculated.

Step 12. Calculate final cost ratings.
Calculate final cost ratings by multiplying the cost ratings by the appropriate weighting factor.

Step 13. Sum of the cost ratings.
Sum cost ratings for each alternative as was done for the effectiveness ratings.

Step 14. Calculate cost-effectiveness scores.
The cost-effectiveness "score" for each alternative is calculated by dividing the sum of the effectiveness measures (Step 8) by the sum of the cost ratings (Step 13) for each alternative. The results of this step provide the final overall cost-effectiveness score for each alternative.

The alternative with the highest scores are those that are most cost-effective.

Step 15. Recalculate trade-off matrix to check sensitivity.

There will be instances in which it will be desirable to assess how the overall cost-effectiveness rankings change if certain elements within the trade-off matrix change. A recalculation of the affected scores will give an indication of the sensitivity of those scores to the changes. Elements of the trade-off matrix that may change are costs, individual ratings or weighting factors. The use of such a sensitivity analysis to assess the changes in overall cost-effectiveness rankings of the alternatives should be considered an essential element of the methodology.

Selection of Preferred Alternative

An example completed matrix is presented in Figure 2. While the cost-effectiveness scores (far right-hand column) are widely different for Options 2 and 3, the differences between 3 and 5 may or may not be significant. While in principal the highest score is the most cost-effective option, a sensitivity analysis would probably confirm that scores close together are essentially equal.

6.0 CONCLUSIONS

The trade-off matrix offers a flexible but structural approach to cost-effectiveness evaluation of remedial action alternatives at uncontrolled hazardous waste sites. The technique can be used in widely varying situations, but can be tailored to meet site-specific needs. Because of its simplicity, the technique is not so time-consuming as to preclude examination of a relatively large number of alternatives. The approach is easily understood by non-technical persons and does not require extensive evaluator education. By relying heavily on the judgements of experts, the method is not dependent on extensive site data, although a good data base undoubtedly improves the confidence level of the evaluation. In addition, the methodology readily allows examination of the sensitivity of the analysis to judgement or assumptions made in the evaluation process.

A possible drawback to this approach to cost-effectiveness evaluation is that the technique may be subject to evaluator bias. However, care in selection of the evaluation team and use of the Delphi technique to deal with outliers in the ratings can minimize this problem. A discussion of the ranking rationale can be supplied to add credibility to the system.

The method is not mathematically rigorous, which may affect its credibility in some cases. In general, the information

		Cost Measures				Site-Independent Effectiveness Measures								Site-Specific Effectiveness Measures					
	Alternatives	Construction	Operation & Maintenance	Other	Σ Cost Ratings	Level of Cleanup/Isolation Achievable	Time to Achieve Cleanup/Isolation	Technology Status	Usability of Land After Action	Capability of Action to Minimize Community Impacts During Implementation	Capability of Action to Minimize Adverse Health & Environmental Impacts During Implementation	Risk and Impact of Failure		Usability of Downstream Lake After Action				Σ Effectiveness Ratings	Σ Effectiveness Ratings / Σ Cost Ratings
	Weighting Factors	1.0	1.2			1.0	0.5	0.6	0.4	0.6	0.7	1.1		0.3					
1	Upgradient Deflection Wall and Cap over Disposal Area	.81	0		.81	2.4	1.1	1.9	1.0	2.0	2.4	3.3		0.8				14.9	18.4
2	Excavate Wastes and Dispose in Secure Landfill	6.0	0		6.0	5.0	2.0	2.6	1.8	1.2	1.1	3.5		1.3				18.5	3.1
3	Collect Contaminated G.W. With Wells from Disposal and Plume Area and Send Water to POTW	.21	.41		.62	2.6	1.0	2.3	0.9	2.2	2.4	3.5		1.2				16.1	26.0
4	Encompass Disposal and Plume Area with Slurry Wall & Cap; Collect G.W. With Wells & Send to POTW	1.33	.41		1.74	4.2	1.4	2.0	1.3	1.7	1.8	2.9		1.2				16.5	9.5
5	Encompass Disposal Area With Slurry Wall & Place Cap over Disposal Area	.65	0		.65	3.0	1.2	1.9	1.0	1.8	2.0	3.5		0.9				15.3	23.5

FIGURE 2

base and prediction capability supporting decisions about remedial actions are insufficient to warrant rigorous quantitative evaluation. To limit evaluation of sites to those with sufficient hard information to support rigorous quantitative analysis could prevent implementation of the NCP.

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SURVEY AND CASE STUDY INVESTIGATION OF REMEDIAL ACTIONS AT UNCONTROLLED HAZARDOUS WASTE SITES

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ABSTRACT

JRB, under contract with the EPA, is in the process of conducting a nationwide survey of uncontrolled hazardous waste sites to identify and examine the various types of remedial action technologies which have been implemented or which are in progress or are proposed as cleanup techniques. At selected sites, detailed case studies will be performed to document the specific reasons for the success or failure of applied remediations technologies and to determine the limitations and applicability of these technologies in other restoration activities or situations.

The results of the case study investigation will be used to provide an information transfer between those who have experienced the implementation of a remedial action and those contemplating or presently assessing or pursuing some form of site cleanup. The anticipated audience, the survey findings, and case study reports include members of industry and commerce, state agencies, local authorities, and the EPA. Case study reports will be structured so that they will provide detailed data on the remediation techniques employed, the circumstances and conditions in which they were implemented, their apparent effectiveness in correcting or controlling the problem, and their potential uses in other natural environments and remedial action situations. Ultimately the survey and case study results will quantify the number and type of reported uncontrolled releases of hazardous substances that have undergone a certain degree of remediation; will provide a standard for comparison when assessing or deciding on a plan for remediation; will identify cleanup technologies which may warrant further research; and most importantly will provide a forum in which others can learn from past miscalculations and successes.

INTRODUCTION

With the passage of the Comprehensive Environmental Response, Compensation, and Liability Act (Superfund) and the publication of the National Contingency Plan, the U.S. Environmental Protection Agency (EPA) has developed a systematic methodology for conducting remedial actions at uncontrolled hazardous waste management facilities. Prior to the passage of Superfund, EPA relied on two laws for providing assistance for remedial actions at uncontrolled hazardous waste sites, the Clean Water Act (Section 311) and the Resource Conservation and Recovery Act.

It is clear from past experiences such as Love Canal that short term and long term environmental and health-related hazards exist when inadequate technologies are used during the handling and disposal of hazardous materials. Presently the Solid and Hazardous Waste Research Division of EPA is involved in the development of existing and novel technologies for use in the remediation of hazardous materials released to the environment. Because new remediation techniques are continually evolving and known technologies are constantly being adapted for remedial action use, the alternatives available for cleanup continue to expand. In order to assess the effectiveness and limitations of these remedial action techniques, EPA is conducting case study examinations of technologies which have been employed in field situations.

Project Description

JRB, under contract with the EPA, is in the process of developing an inventory of uncontrolled hazardous waste sites to identify and examine the various types of remedial action technologies which have been implemented, are in progress, or are proposed as cleanup techniques. In addition, detailed case studies will be performed at selected sites in order to document the specific reasons for the success or failure of applied remediations technologies and to determine the limitations and applicability of these technologies.

The results of the case study investigations will provide information to those contemplating, presently assessing, or pursuing some form of site cleanup. The anticipated audience includes members of industry and commerce, state agencies, local authorities, and the EPA. Case study reports will be structured so that they will provide detailed data on the remediation techniques employed, the circumstances and conditions in which they were implemented, their apparent effectiveness in correcting or controlling the problem, and their potential uses in other natural environments and remedial action situations. Ultimately the survey and case study results will quantify the number and type of reported uncontrolled releases of hazardous substances that have undergone some degree of remediation; will provide for comparison when assessing or deciding on a plan for remediation; will identify cleanup technologies which may warrant further research; and most importantly will provide a forum in which others can learn from past experiences.

Survey Method

The initial survey task was to compile an updated list of uncontrolled hazardous waste sites which included both ongoing and completed remedial actions. The sources of information used to compile this list included: in-house literature review of selected documents; data from EPA Municipal Environmental Research Laboratory (MERL) and Office of Emergency and Remedial Response (OERR); remedial action programs and site studies; EPA Headquarters and Regional contacts with knowledge of remedial actions projects, including work at Superfund sites; Department of Defense (DOD) contacts with knowledge of restoration work at military bases; State environmental and health agencies involved in site remedial actions; and industrial and pertinent trade association contacts involved in spill responses or hazardous substances cleanups.

The inventory began by conducting a review and updating data on the 199 sites identified by SCS Engineers (1), and the data contained within the list of 114 Top-Priority Superfund Sites (2). Simultaneously, in-house files and publications, including the Groundwater Newsletter, Hazardous Waste Reporter, and Hazardous Materials Report, were reviewed to identify any sites not contained in the SCS Report or Superfund list. Once the data review was completed, EPA regional, state, and local parties identified as being knowledgeable in hazardous site remediation activities were contacted to supplement information collected from the internal survey and to expand the site data base. Knowledgeable parties contacted included EPA Regional Emergency Response Coordinators, Regional Land Disposal Branch personnel, Regional On-Scene Coordinators, State On-Scene Coordinators, consulting contractors, site managers and operators, Department of Defense, and state and local officials.

Cooperation was also solicited from trade associations representing industries which may have been involved in hazardous waste management, generation, or transportation and from firms specializing in the design and implementation of remedial actions at hazardous materials spills sites and waste management facilities.

Approximately 300 additional sites were identified. Data collected on the sites included the name and location of the site, the remedial actions implemented or planned, the type of waste management practices used at the facility, the waste types/contaminants present, the availability of engineering cost data, and the ease of access for a case study. A clear majority of the sites surveyed were obtained from two data sources, the SCS Report (1) and the list of 114 Top-Priority Superfund Sites (2). However, contacts made during discussion with responsible parties involved in remediation activities at the Superfund sites and SCS sites often led to discovery of sites not previously listed.

The results of the DOD effort indicate that remediation activities within the armed forces are in the initial stages. DOD has established a phased approach for conducting site restoration activities within all branches of the Armed Forces. Presently, each branch of DOD is proceeding at individual rates and in most cases have conducted initial site assessments but have not initiated any site restoration activities.

Contacts with several cleanup firms, consultants specializing in remedial alternative design, and trade associations, led to the discovery of several sites. However, in most cases client confidentiality agreements hindered full cooperation in identifying sites. It is reasonable to assume that the many private sector cleanups are completed but are not reported. Therefore these are not included.

Once the site survey activities were completed, criteria were established to select candidate sites for detailed case study analysis. These criteria included:

- o Availability for field survey activities
- o Availability, accessibility, and completeness of remedial action cost and engineering data
- o Type of remedial action technology implemented, so that a range of remedial action techniques were investigated
- o Type of waste management practice, so that a wide range of technologies common to hazardous waste management were studied
- o Types of waste and contaminants present at the facility to ensure that a variety of waste streams and pollutants were included
- o Hydrogeologic setting, so that a variety of settings were represented
- o Geographic location to provide a nationwide distribution of sites.

Approximately 20 sites have been identified for case study analysis and field surveys for these sites are presently being performed.

Survey Results

Three hundred and sixteen sites have been identified with some form of completed, ongoing, or planned remediation activity relative to the uncontrolled releases of hazardous substances to the environment (Table 1). This is a substantial increase in the number of sites identified in a similar survey conducted in 1980 (3). Two key factors can explain the increased number of identified sites; these are:

- o The data base used in the 1982 survey was an expanded version of the 1980 data base, including contact with the Department of Defense, pertinent trade associations, industrial contacts, and cleanup contractors, and
- o Additional data relative to hazardous waste sites has been made available through the EPA Field Investigation Team activities over the past two years and there has been incresed awareness by state and local officials relative to site discovery and identification.

Although the number of identified sites has increased by 147 the percentage of sites located in the individual states has not changed appreciably. It is also apparent that a majority of sites identified are concentrated in the heavily industrialized regions of the country. This corresponds well with the economics and convenience of disposing of waste materials near the generating source.

TABLE 1. STATE LOCATION OF REMEDIAL ACTION SITES IN 1980 AND 1982

State	Number of Sites '80	Percent of Total Identified Nationwide '80	Number of Sites '82	Percent of Total Identified Nationwide '82
Alabama	2	1.2	2	0.6
Alaska	0	0	0	0
Arizona	3	1.8	6	1.9
Arkansas	2	1.2	4	.3
California	3	1.8	9	2.8
Colorado	3	1.2	5	1.6
Connecticut	4	2.4	11	3.5
Delaware	2	1.2	4	1.3
Florida	7	4.1	26	8.2
Georgia	4	2.4	5	1.6
Hawaii	0	0	0	0
Idaho	0	0	0	0
Illinois	8	4.7	14	4.4
Indiana	3	1.8	4	1.3
Iowa	1	0.5	2	0.6
Kansas	2	1.2	3	1.0
Kentucky	5	3.0	6	1.9
Louisiana	3	1.8	9	2.8
Maine	2	1.2	3	1.0
Maryland	1	0.5	3	1.0
Massachusetts	5	3.0	11	3.5
Michigan	11	6.5	13	4.1
Minnesota	3	1.8	8	2.5
Mississippi	0	0	3	1.0
Missouri	4	2.4	10	3.2
Montana	5	3.0	5	1.6
Nebraska	0	0	0	0
Nevada	0	0	1	0.3
New Hampshire	1	0.5	6	1.9
New Jersey	10	5.9	17	5.3
New Mexico	0	0	3	1.0
New York	14	8.3	29	9.2
North Carolina	7	4.1	8	2.5
North Dakota	6	3.6	6	1.9
Ohio	4	2.4	5	1.6
Oklahoma	0	0	3	1.0
Oregon	0	0	0	0
Pennsylvania	16	9.4	23	7.3
Rhode Island	4	2.4	5	1.6
South Carolina	3	1.8	5	1.6
South Dakota	0	0	2	0.6
Tennessee	10	5.9	10	3.2
Texas	3	1.8	7	2.2
Utah	1	0.5	2	0.6
Vermont	0	0	1	0.3
Virginia	2	1.2	4	1.3
Washington	0	0	5	1.6
West Virginia	1	0.5	2	0.6
Wisconsin	3	1.8	5	1.6
Wyoming	1	0.5	1	0.3
Total 50 States	169		316	

Table 2 is a compilation of the various types of disposal methods employed at the sites identified during the survey. The data collected from approximately 30 of the sites does not allow an accurate assessment of the disposal method used. Therefore, these sites were eliminated from Table 2 (4).

Waste management practices and contaminant releases identified during the survey include land disposal, drum and tank storage, incineration, and treatment, subsurface injection, spills and illegal dumps. Data indicate that 78 percent of the facilities where remedial actions were either completed, ongoing, or planned can be associated with three waste management technologies: landfilling, drum storage, or surface impounding. This association is to be expected since these technologies have been the most common methods over the years for managing and disposing of hazardous substances. The relatively low percentage of incinerators and injection wells identified in the survey can be attributed to the limited applicability of these technologies for treating and disposing of a wide spectrum of hazardous materials, and to their limitations for use in broad geographic and environmental regions. The low percentages of illegal dumps identified can be associated with the expected unavailability of data necessary to sufficiently characterize these facilities.

The remedial technologies used at the surveyed sites included capping and grading, removal and offsite burial, groundwater pumping, chemical and biological treatment, and containment and encapsulation (Table 3). However, 76 percent of the remediating efforts identified involved four techniques: capping/grading, drum removal, contaminant removal, or contaminant treatment. In most instances, these techniques correlate well with the high percentage of facilities identified as practicing landfilling, drum storage, or surface impounding as a waste management method. This correlation is based on the following factors:

- Most remedial actions to date have been directed at controlling the immediate threat, i.e. removal of the waste material and contaminated soil, surface impoundment pumping and removal, or drum removal
- Technologies such as grading/capping, contaminant removal, and drum removal are in most cases relatively unsophisticated and inexpensive remedial activities when compared with other remedial options
- Removal of the contaminant source is the most likely initial step in performing a staged facility cleanup
- Complete removal of the source of contamination is the most direct method of reducing or eliminating continued releases of contaminants to the environment.

TABLE 2. TYPES OF DISPOSAL METHODS

Disposal Methods	Number of Sites	Percent of Total
Landfill	121	32
Drum Storage	67	18
Surface Impoundment	104	28
Spills	25	7
Incinerator	10	3
Injection Wells	8	2
Illegal Dumps	39	10
TOTAL	373	100%

*In some cases, more than one disposal method has been used at an individual site.

TABLE 3: TYPES OF REMEDIAL ACTION EMPLOYED

Remedial Action	Number of Sites	Percent of Total
Capping/Grading	59	19
Drum Removal	56	18
Contaminant Removal	70	23
Groundwater Pumping	22	7
Groundwater Containment	23	8
Contaminant Treatment	48	16
Encapsulation	8	3
Dredging	5	2
Gas Control	3	1
Incineration	3	1
Lining	7	2
TOTAL	304	100%

*In some cases, more than one remedial action technique has been used at an individual site.

Less often used methods of site remediation include encapsulation, dredging, incineration, groundwater containment or pumping, and subsurface gas control. Several reasons exist for the limited use of these methods as remediation techniques, these include:

- Constraints based on site specific conditions such as waste type, area of contamination, and media contaminated
- Present level of technological development relative to proven field use and successful application in real world situation
- Effects of economic and institutional factors which limit the availability of funds, or requirements for specific approaches to be used in resolving the cleanup problem (i.e., emergency cleanup vs. long term cleanup).

Based on the information gathered on the restoration activities of relatively new sites there has been a shift in the approach historically used to plan and implement remedial actions. In more recent times, emphasis has been placed on thoroughly understanding the dynamics of the contamination and then developing and implementing the remedial action program. The shift to more systematic approaches in planning remedial actions can be attributed to more comprehensive regulations relative to hazardous waste management and the assignment of strict site cleanup liabilities and responsibilities (i.e., Superfund and the Resource Conservation and Recovery Act), and also to lessons learned from successful and unsuccessful cleanup methods and techniques employed in the past.

Case Studies

Once the case study sites were selected, field activities were conducted to collect additional information to ensure the development of accurate and complete case history reports. Field visits included trips to the sites as well as meetings with the appropriate Federal, State, and private parties involved in the site remediation. The following is a brief synopsis of three case study investigations.

Trammel Crow Site - Dallas, Texas

The first case study was a former Texaco oil refinery which operated in Dallas, Texas from 1915-1945. When the refinery ceased operation, it was sold to a metal recycling firm which reclaimed any valuable scrap metal on site. The property was left vacant for twenty years after the scrapping operation until it was sold in 1980 to the Trammell Crow Corporation for industrial development. At the time of purchase, five waste sludge pits with over five million gallons of still bottoms and other petroleum refinery wastes were located on the site. The five ponds were not all the same size and did not contain the same materials. One pond, the largest, contained approximately 3.5 million gallons ($16,600/yd^3$) of crude oil tank bottoms consisting of 50 percent carbonaceous material, 35 percent water, and 15 percent ash. The carbonaceous portion of the sludge was made up of equal portions of asphaltenes and paraffins. A second contained approximately $10,000/yd^3$ of hard coke/slag material believed to be coke cinders from the petroleum refinery cracking process. The remaining three ponds contained approximately 1.5 million gallons of sedimentation or oxidation pond oily residues.

The waste ponds were located above a Trinity Clay soil which extends to a depth of 20 to 45 feet below the ground surface. The Trinity Clay is a moderately alkaline soil of low permeability (less than 4.2×10^{-5} cm/sec). This in turn, overlies an Eagle Ford shale which extends to a depth of approximately 400 feet below the surface. The Trinity Clay and Eagle Ford shale formations form an impermeable barrier between the surface and the underlying aquifer, therefore the potential for groundwater contamination is low.

The wastes were tested for toxicity using the EPA required extraction procedure defined by RCRA. The sludges were not found to be hazardous. However, the sludges in the ponds had to be treated and/or removed before property development could take place. Although the waste oil was not a RCRA hazardous waste, it was classified under Texas law as Class II industrial waste and could not be put into a municipal landfill. The costs of transporting the sludge to the closest industrial waste landfill were much greater than the alternative devised: solidification and disposal of the sludge in an approved site. Although the remedial approach was used for a nonhazardous waste oil, it is apparent that the same process could also be applied to similar sites where oil waste sludges are defined as hazardous wastes under RCRA.

The technology chosen was a sludge solidification process using cement kiln dust available locally. Instead of using only fresh kiln dust (which is limited in supply because of outstanding contracts for the material) to mix and solidify with the sludge, a stale kiln dust was also used. The stale dust, which is 38 percent moisture and stockpiled in large quantities, is less expensive and is a very effective solidifying agent (5).

The solidification procedure began with the three smaller ponds using stale cement kiln dust. A landfill was excavated next to the three ponds. Stale cement kiln dust was delivered to the bottom of the landfill and leveled by bulldozer into a 6 to 12 inch layer. A backhoe lifted the sludge out of the pits and it was then placed on top of the kiln dust in the landfill. The bulldozer then mixed the dust and the sludge into one foot layers with 3:1 and 2:1 dust to sludge ratios. A pulverizing mixer was then driven over the one foot layer to completely homogenize the mixture. Each layer was air dried for approximately one day and then compacted and field tested to ensure proper compaction. This procedure continued until the contents of all three ponds were solidified in the landfill.

For the largest pond, solidification was somewhat different as the sludge was more liquified and the pond itself was several thousand feet from the landfill. Because of its liquified nature, the sludge was solidified using both fresh and stale kiln dust. The procedure for solidifying the sludge incorporated the same layering process used for the three small ponds, however, the sludge was treated prior to placement in the on-site landfill. Fresh cement kiln dust was blown into the sludge pond using a ratio of 1.5:1 dust to sludge. A backhoe mixed the dust to form a semi-solidified sludge. The semi-solidified sludge was transported to the on-site landfill, unloaded onto a bed of stale kiln dust, and mixed as previously described. As each side of the pond was excavated, it was backfilled with clean dirt until all of the sludge had been removed and solidified in the on-site landfill. The coke/slag material was also removed from the remaining pond and mixed in with the sludge in the on-site landfill.

This entire process took approximately 41,000 tons of kiln dust. This was much less than originally anticipated because the stale kiln dust solidified with the sludge better in the field than in the laboratory. The projected cost of $500,000 had been based on an estimated use of 75,000 tons of kiln dust, however, the project cost only $377,528. This was much less than the alternative of off-site disposal which was estimated to cost $1,500,000.

Presently, the site is completely solidified, graded over, and covered with vegetation. It is awaiting sale for future development.

Goose Farm Site - Plumsted Township, New Jersey

The Goose Farm site is an abandoned hazardous waste drum burial site that was partially cleaned up during the one-year period from August 1980 to November 1981. The drum burial site is located in Plumsted Township, Ocean County, New Jersey in a region known as the Pinelands, a unique ecological area characterized by acidic sandy soils and low-lying forests of pine and oak.

From about 1945 to the mid seventies, Thiokol Corporation (a manufacturer of ammunition, rocket fuel, plastics, and organic fibers) dumped bulk and containerized hazardous wastes into a pit about 300 feet long by 50 feet wide by 15 feet deep, under contract with the site owner. January 1980, township officials informed the New Jersey Department of Enviromental Protection (DEP) of the existence of hazardous wastes at the Goose Farm site. Shortly, thereafter, DEP conducted a preliminary investigation of the site, which revealed the discharge of contaminated groundwater as a surface seep to a nearby stream. During the next six months, site activities included sampling of the stream and groundwater from 17 monitoring wells, conducting metal detector and resistivity surveys, and reviewing regional geological data and well driller logs.

A report assessing the situation at Goose Farm was submitted in June 1980, which described a contaminated groundwater plume about 200 feet wide originating from the drum burial area and moving into the stream where it was discharging. The plume was also believed to be moving downward because of the geology in the area. Preliminary testing was inconclusive, but suggested potential contamination of up to 60 feet in depth beneath the site, with the majority of contamination occuring within a depth of 40 feet. Monitoring of the upper groundwater and surface seepage indicated the presence of a large variety of inorganic and organic solvents, and pesticides. Levels of contaminants were highest for methylene chloride, benzene, and toluene, in the 100 ppm range. Total organic carbon ranged from 1,600 to 17,000 ppm. The investigation also indicated that the plume was not an immediate danger to any drinking water wells in the area, but if uncorrected could cause widespread contamination of the lower strata, a moderately used aquifer.

The State established the following objectives and hired an oil and hazardous waste cleanup contractor to carry out the following:

- Obtain data to determine the extent of contamination of the surface water and groundwater
- Contain the discharge to the stream by pumping and treating the groundwater
- Remove the source of pollution, i.e. buried wastes and contaminated soil
- Further groundwater removal and treatment near the source area.

Temporary containment measures (such as the installation of an open or gravel-filled cut-off trench) were suggested but were not implemented.

Cleanup efforts consisted of constructing a well-point treatment system to prevent the contaminant plume from discharging into the stream; and excavating, segregating, and treating the buried waste materials in the disposal area. The well-point system was located between the disposal area and the stream and was oriented in such a way as to intercept the contaminant plume. The well-point system consisted of about 400 feet of six inch aluminum header pipe with 100 well-points spaced about every 7.5 feet. The well-points were installed to a depth of 22 feet by water jetting. The system was pumped at a rate of about 50,000 to 75,000 gallons per day to contain migration of the contaminants.

The collected groundwater was routed to a treatment system consisting of the following:

- A vacuum receiver which volatilized about 20 percent of the total organic carbon (TOC) in the stream
- Carbon adsorbers to treat the gaseous stream of the vacuum receiver
- A clarifier which reduced suspended solids and removed about 10 percent of TOC in the stream
- Multi-stage carbon absorbers which removed about 70 percent of the initial TOC.

The final effluent after treatment had a total organic carbon concentration of about 54 mg/l, a reduction of 96.6% to 99.7% in TOC. After treatment, the effluent was spray irrigated.

Concurrently waste removal operations were carried out in the pit area. During a 45-day period, over 4,880 drums and containers were excavated, analyzed, secured, and segregated. A backhoe and two specially designed drum grapplers were used to complete removal operations. Salvagable drums were overpacked and stored on-site. Badly degraded drums were tested for acid-base compatability and emptied into concrete holding tanks prior to disposal. In addition, about 3,500 tons of contaminated soil were excavated and stored temporarily awaiting disposal.

After the drum pit area had been excavated, a second well-point system was installed in the pit area. Groundwater was pumped to the treatment system and the effluent was injected into the pit area via injection well-points to flush contaminants from the underlying soils. The extraction well-points were first installed in the unsaturated zone to a depth of 7 to 13 feet and later lowered into the water table to collect groundwater contamination.

The groundwater treatment system was shut down in March 1981 before treatment was complete because of operating expenses. Secured drums, bulked liquids, and contaminated earth were stored on site from March 1981 to November 1981, awaiting funds for final disposal. In November 1981, 4,400 tons of waste were transported in 200 trucks loads to an approved waste disposal site. In addition, 12 drums of PCB's were transported to an approved hazardous waste incinerator.

Stroudsburg Site - Stroudsburg, Pennsylvania

The Stroudsburg site is located in the borough of Stroudsburg, Monroe County, Pennsylvania, along the shores of Brodhead Creek at the site of a historical coal gasification plant once operated by Stroudsburg Gas Co.

From the late 1800's to the early 1900's, one of the disposal methods practiced on site for the disposal of coal tar residuals was the injection of the waste material into the ground through an injection well located in the northwestern quadrant of the plant property. The well was constructed such that the waste products were injected into the gravel alluvium that underlies the plant area, approximately 20 feet below the surface.

In 1947, Pennsylvania Power and Light Company PP&L) purchased several parcels of land from Stroudsburg Gas Co., most of which were located along the shores of Broadhead Creek. In October 1980, during maintenance construction of the flood control levees along the western shore of Brodhead Creek, a black, odorous material was observed seeping from the base of the dike at several locations along the side of the stream.

The incident was reported to the Pennsylvania Department of Environmental Resources (DER), Bureau of Water Quality and investigations commenced to determine the nature and extent of the contamination. A preliminary assessment of the situation was made in March 1981 and at this time the DER requested the assistance of the EPA in the further investigation of the problem. The investigative field studies that followed were conducted by DER, EPA and the Pennsylvania Fish Commission (PFC) and involved the following the areas:

- The hydrogeology of the site area
- The impact of the coal tar on stream quality and its biological community
- The erosional behavior of the stream.

The remedial actions that were taken at the Stroudsburg site involved several technologies. The initial remedial response to the problem was conducted by EPA in April 1981 under section 311 of the Clear Water Act (Public Law 92-500) and involved the installation of filter fences, sorbent booms and inverted dams. These were temporary structures were constructed to prevent direct and immediate coal tar seepage into Brodhead Creek.

As field investigations continued, it was concluded that actions permissible under section 311 (i.e., emergency, oil spill response actions) would not sufficiently remedy the pollution problem at the Stroudsburg site. A more reliable and permanent remedial system was necessary. Beginning on November 9, 1981, funds were appropriated under Superfund.

In November 1981, PP&L began installation of a recovery well system to remove the coal tar from the stratigraphic depression existing behind the west bank levee. An estimated 35,000 gallons of coal tar had accumulated in the depression. The project was completed in late spring of 1982 and consisted of four well clusters each containing four wells. Presently only one central well of one of the clusters is in operation and the recovery rate is less than had been anticipated. The original recovery rate predicted was approximately 100 gallons per day. The present rate is between 20-25 gallons per day. This situation was primarily caused by an overestimation of the quantity of concentrated coal tar present. Much of what exists is actually a mixture of coal tar and water, which was not realized until the wells had already been installed. Approximately 7,500 gallons of pure coal tar (95%) have been recovered to date. The recovered residue is sold to Allied Chemical in Detroit, MI, where it is used as fuel.

Concurrent with PP&L's project, EPA constructed a cement-bentonite, slurry trench, cut-off wall along the west bank levee. The containment wall is 648 feet long, one foot wide and 17 feet deep. The downstream end of the barrier is horizontally keyed into an impermeable curtain formed by pressure grouting. The upstream end is keyed into the sheet piling wall that exists below the concrete flood wall. The slurry wall extends over the area of observed seepage and passes vertically through the gravel layer that bears the contaminant and is keyed two feet into the underlying sand stratum. A total of eight monitoring wells were installed for monitoring slurry wall performance and sampling groundwater in the area. Four wells are located on either side of the wall.

In January 1982, following slurry wall construction and the installation of the monitoring well system, the contaminated material was excavated, drummed, and disposed of at a secure landfill. Throughout all the activities undertaken at the Stroudsburg site, materials meant for disposal were packed in drums and stored on site until appropriate disposal sites were located.

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FIELD SCHEME FOR DETERMINATION OF WASTE REACTIVITY GROUPS

Preliminary Investigation

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ABSTRACT

Remedial action at hazardous waste disposal sites requires procedures to predict the potential consequences of mixing waste materials from separate sources. Previous procedures have assumed a prior knowledge of the chemical composition of the waste materials. The need for small scale mixing as a safeguard prior to large scale mixing is emphasized even when the chemical composition of two waste materials indicates compatibility.

A test scheme has been devised, based upon standard qualitative test procedures, which will enable workers in the field to determine the gross chemical composition of waste materials. Chemical composition information obtained from these tests is used to classify waste materials into reactivity groups, and thus predict compatibility characteristics. The test scheme includes a field test kit, a series of flow diagrams, and a manual for using the flow diagrams and test procedures. In addition, a simple device to observe the effects of mixing two hazardous waste materials has been assembled and is included in the field test kit.

The test scheme is broken into six procedure sets. Each of the procedure sets consists of a series of simple tests and acts as a step in the classification of an unknown waste material. The test procedures have been verified experimentally by applying the tests directly to a group of 57 compounds, chosen to represent a wide variety of hazard classes. The information provided in this manuscript is in support of the U.S. Environmental Protection Agencies implementation of PL-96-510, Comprehensive Environmental Response Compensation and Liability Act.

INTRODUCTION

During remedial action at an abandoned waste disposal site, it is frequently necessary to ascertain whether waste materials from two sources can be mixed safely for purposes of bulking, recontainerization, shipment, and ultimate proper disposal. The history of hazardous waste management contains numerous accounts of disasters resulting from the mixing of incompatible wastes. Proper management of hazardous waste therefore requires test procedures for identification of potential reactivity hazards so that consequences of mixing of hazardous wastes can be predicted and undesired reactions resulting from the mixing of two wastes can be avoided.

The document "A Method for Determining the Compatibility of Hazardous Wastes" (1) classifies wastes by chemical class and/or general reactive properties and lays out a sequence of activities to determine the compatibility of two wastes. The key elements of this document are a compatibility chart and a flow diagram for its use. However, the aforementioned document presupposes a knowledge of the composition of the waste materials. This information is often available from generators of hazardous waste, but during remedial action at an abandoned site, it is seldom available. The need to test mix two wastes on a small scale is emphasized even if the compatibility chart indicates compatibility.

PURPOSE

It is the purpose of this study to establish sequences of simple test procedures that will enable workers in the field to classify hazardous wastes according to their chemical reactivity when no prior knowledge is available regarding their composition. The chemical reactivity classifications (reactivity groups) are then used to predict which waste materials can be mixed safely by applying the compatibility chart in reference 1. A field test kit will be assembled which contains all necessary equipment and reagents for performing the reactivity tests. The kit will include a simple device to conduct actual mixing tests on waste materials shown to be compatible according to the classification scheme.

Because of the environment in which these classification test procedures will be utilized, there are certain desirable limitations on the schemes, test procedures, and equipment to be used. Limitations that are being specifically addressed during the course of this study are as follows:

- The procedures must be safe and easy to perform by non professionals. To maximize the safety of the test procedures, only small amounts of the test materials are being used, and materials of extreme reactivity are identified early in the testing sequence. The simplicity of the test procedures will be verified by using nonprofessionals to perform the tests in the later part of the program.
- The procedures must give definitive, objective results. Test materials are analyzed as unknowns to verify objectivity of observation.
- The equipment must be standard, readily available, portable, and require minimal utility hookups, since the tests will be applied in remote field locations. For this reason, the test equipment is entirely self-contained (i.e., requires no utility hookups, etc.).
- The procedures will need to be performed as rapidly as possible, since numerous waste samples will require testing. For this reason, abbreviated classification schemes are proposed as a time saving measure.
- The test procedures must be able to be performed with slightly restricted manual dexterity, since they may be performed in areas where protective clothing is required.
- The test procedures must be reproducible.

SCOPE

A set of 57 test compounds were selected from a listing (Appendix 2 of Reference 1) of materials likely to be found in hazardous waste disposal facilities. The compounds were selected to represent as broad a range of chemical reactivity as possible. All but one of the reactivity groups from the compatibility chart (1) is represented by the 57 test compounds. A list of the test compounds and assigned reactivity groups are shown in Table 1.

Test procedures were identified from literature sources (2, 3, 4, 5, 6) and arranged into test schemes to classify waste materials into reactivity groups. The test procedures are applied to the 58 test compounds. In the development of the test schemes, each of the test procedures was applied to the test compounds and results were compared to those expected. The test schemes and procedures were then applied to the 57 test compounds anonymously and the results were used to classify the "unknown" test compounds into reactivity groups.

All equipment and reagents used in the test schemes is being assembled into a field test kit. A manual for the use of the test schemes, including detailed

TABLE 1. TEST COMPOUNDS FOR HAZARDOUS WASTE COMPATIBILITY TESTING

	Reactivity Group Number (RGN)																																							
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	101	102	103	104	105	106	107
Acrolein					X																																X				
Aldicarb									X											X																					
N-Butyl acrylate													X																												
Diacetone alcohol				X															X																						
Ethyl acrylate													X																								X				
Fluoroboric acid	X														X																										
Hexafluorophosphoric acid	X														X																										
Potassium cyanide											X																														
Hydrofluoric acid	X														X																										
Hydroxyacetophenone																			X												X										
Lannate									X											X																					
Mercaptobenzothiazole																				X																					
Mercaptoethanol				X																X																					
Methyl methacrylate													X																								X				
Peracetic acid			X																											X											
Polypropylene																												X							X						
Polysulfide polymer																				X															X						
Propylene oxide																																		X			X				
Vinyl acetate													X																								X				
Selenium diethyldithiocarbamate												X												X																	
TEPA						X																										X									
Ziram												X												X																	
Arsenic pentasulfide																								X									X								
Cadmium																							X	X																	
Chromium																							X	X																	
Copper																							X	X																	
Lead																							X	X																	
Nickel																						X		X																	
Trinitro benzoic acid			X																								X									X					
Ethylene glycol monomethyl ether				X										X			X																								
Styrene																X												X								X					
Chlorophenyl isocyanate																	X	X																							X
Bromoxynil																	X									X					X										
Chromic anhydride		X																						X														X			
Dipicryl amine							X																				X									X					
Barium																					X			X																	X
Sodium																					X																		X		X
Barium iodide																								X																	
Barium oxide										X														X																	X
Picric acid																											X				X					X					
Acetamide						X																																			
Aminopropionitrile							X																			X															
Aminothiazole							X																																		
Benzoyl peroxide																														X						X					
Calcium hypochlorite																																						X			
Decane																													X												
1-decene																												X													
Dimethylaminoacobenzene							X	X																																	
Diphenamid						X																																			
Hexane																													X												
1-hexene																												X													
Hydroxylamine hydrochloride																																							X		
Malathion																																X									
Malonic nitrile			X																							X															
Naphthalene																X																									
Parathion																																X									
Toluene diisocyanate																		X																							
Totals by class	3	1	3	3	1	3	4	3	2	1	1	2	4	1	3	2	3	2	2	5	2	1	4	12	0	3	3	4	2	2	3	3	1	1	2	5	5	2	2	0	4

instructions for conducting the test procedures and directions for use of the flow diagrams, is included in the kit also.

A mixing device has been assembled and is being evaluated for its ability to detect reactivity by gas and heat evolution. The design of the device is a simplified version of similar devices reported earlier in the literature (6, 7).

At the conclusion of the study, the field test kit will be employed in a 1-week field evaluation at the EPA Combustion Research Test Facility located in Jefferson, Arkansas. The tests will be applied to several "real" wastes during the field evaluation.

DISCUSSION OF TEST PROCEDURES

Test Procedures

A series of test procedures has been assembled which can be used to classify hazardous wastes based upon their gross chemical composition. These test procedures are based upon established qualitative chemical tests (2, 3, 4, 5). Specific functional group tests have been identified for all but four of the 41 reactivity groups (RGN's) listed in Reference 1. A complete listing of tests by reactivity group is presented in Table 2. Details of the test procedures are lengthy and therefore do not warrant a full description here. Instead, procedural references are also given in Table 2. However, general comments concerning some nonspecific test procedures warrant brief discussion. Personal protective equipment required for these procedures will be utilized.

Physical examination of the waste material reveals the phase (liquid, sludge, solid) and may give clues about the material present (elemental metals, for example). Paper tests are conducted to test for pH (pHydrion paper) oxidative potential (iodide-starch paper) and reductive potential (methylene blue paper). Liquids are tested by direct application to the test paper. Solids are tested by applying the solid to wet paper, by applying an aqueous solution of the material to the test paper, or by applying a solution of the material in organic solvent to the paper, drying the solvent, and wetting the paper with water. (CAUTION: Care should be taken when wetting an unknown solid with water.)

Ignition (flame) tests are performed using a small crystal or droplet of material on a nichrome wire. The material is held near the flame, then gradually brought into the flame until a response is noted. Larger amounts are tested using a porcelain spoon where further testing is indicated.

Solubility-reactivity tests are performed by placing a small amount (a few drops or equivalent) of the waste material in the depressions of a porcelain spot plate. These portions of waste are treated with a few drops each of water, hydrochloric acid, nitric acid, sulfuric acid, 3M sodium hydroxide, methanol, acetone, hexane, and toluene. Concurrent with these tests, liquid wastes are tested for the presence of water with anhydrous copper sulfate, and tests are performed for sulfide (lead acetate paper) and cyanide (Table 2).

Functionality tests are used as a final assignment of waste materials into reactivity groups, based upon the functional groups present. The tests are established qualitative organic and inorganic procedures, and are referenced in Table 2. (Warning: The limits of detection of these tests in some cases may not be sufficient to identify trace quantities of materials, e.g., cyanide concentrations that could be hazardous to personnel).

The procedures have been organized into a visual examination phase and six "procedure sets (PS)", as outlined below:

- PS 1 -- pH and redox tests to identify acids, caustics, oxidizing and reducing agents
- PS 2 -- Solution-reactivity and special functionality tests to determine reactivity and/or solubility in a series of acids and solvents and identify the presence of water, sulfide and cyanide
- PS 3 -- Flame tests to identify combustible (organic) and

TABLE 2. SUMMARY OF SPECIFIC TEST PROCEDURES

RGN	Reactivity group name	Name of test*	Reference
1	Acids, mineral, nonoxidizing	pH	Paper test
2	Acids, mineral, oxidizing	pH, oxidation	Paper tests
3	Acids, organic	pH, flame	Paper test
4	Alcohols and glycols	Vanadate-quinolinol	4, p. 172
5	Aldehydes	Dinitrophenylhydrazine, Schiff's test	2, p. 264-65
6	Amides	Oxamide test	4, p. 264-65
7	Amines, aliphatic and aromatic	p-Nitrobenzenediazonium tetrafluoroborate	2, p. 237
8	Azocompounds, diazo compounds and hydrazines	Dimethylaminobenzaldehyde, glutaconic aldehyde	4, p. 666 4, p. 269
9	Carbamates	Diphenylcarbohydrazide	4, p. 390
10	Caustics	pH	Paper test
11	Cyanides	Chloramine-T	5, p. 380
12	Dithiocarbamates	Copper chloride-acetic acid	4, p. 304-05
13	Esters	Hydroxamate	4, p. 214
14	Ethers	Iodine test	2, p. 267
15	Fluorides, inorganic	Zirconium alizarinate	4, p. 420
16	Hydrocarbons, aromatic	Friedel-Crafts test + ferrox test	2, p. 233-34 2, p. 231-32
17	Halogenated organics	Sodium fusion	2, 173, 177-180
18	Isocyanates	. . .	. . .
19	Ketones	Dinitrophenylhydrazine, Schiff's test	2, p. 264-65
20	Mercaptans and other organic sulfides	Lead acetate	2, p. 274

(continued)

TABLE 2. (continued)

RGN	Reactivity group name	Name of test*	Reference
21	Metals, alkali and alkaline earth, elemental and alloys	H_2O, HCl, phosphomolybdic acid	3, p. 362
22	Metals, other elemental in the form of powders, vapors, or sponges	Phosphomolybdic acid	3, p. 362
23	Metals, other elemental, and alloys as sheets, rods, moldings, drops, etc.	Phosphomolybdic acid	3, p. 362
24	Metals and metal compounds, toxic	Zinc sulfide, ammonium sulfide	3, p. 84
25	Nitrides	. . .	. . .
26	Nitriles	Oxamide test	4, p. 264-65
27	Nitro compounds	Tetrabase fusion	4, p. 295
28	Hydrocarbon, aliphatic, unsaturated	Baer's test, ferrox test	2, p. 162 2, p. 231-32
29	Hydrocarbon, aliphatic, saturated	Ferrox test	2, p. 231-32
30	Peroxides and hydroperoxides, organic	Potassium iodide - starch	4, p. 615
31	Phenols and cresols	Ferric chloride test, p-Nitrobenzenediazonium-tetrafluoroborate	2, p. 228, 2, p. 237
32	Organophosphates, phosphothioates and phosphodithioates	Sodium fusion	2, p. 173 ff
33	Sulfides, inorganic	Lead acetate	Paper test
34	Epoxides	. . .	. . .
101	Combustible and flammable materials, miscellaneous	Flame test	2, p. 160-61
102	Explosives	Flame test	2, p. 160-61

(continued)

TABLE 2. (concluded)

RGN	Reactivity group name	Name of test*	Reference
103	Polymerizable compounds	. . .	. . .
104	Oxidizing agents, strong	Iodide, starch	Paper test
105	Reducing agents, strong	Methylene blue	Paper test
106	Water and mixtures containing water	Copper sulfate	2, p. 161
107	Water reactive substances	Water spot test	Spot test
		Other Test Procedures	
Organic	All RGN's	Ferrox test	2, p. 231-32
Organic	All RGN's with heteroatoms (N, O, P, S, X)	Sodium fusion	2, p. 172 ff
All	All RGN's	Flame test	2, p. 160-61

*WARNING: The detection limits of these tests, in some cases, may not be sufficient to identify trace quantities of materials.

extremely heat-sensitive (explosive) materials (additional "indicators" of composition may also be obtained)

- PS 4 -- Ferrox and sodium fusion tests to provide elemental analysis for organic waste materials
- PS 5 -- Functional group tests for specific identification of organic functional groups (RGN's)
- PS 6 -- Functional group tests for specific identification of inorganic RGN's

The procedure sets have been organized into a master scheme for examination of unknown waste materials. The organizational sequence of procedure sets into a general scheme and the organization of tests into procedure sets are discussed in subsequent sections.

Procedures Sequence

The test procedures are organized into a scheme for the classification of unknown hazardous wastes into reactivity groups. Preliminary procedures classify the material as acid, base, oxidizing, reducing, or water-reactive, and primarily organic or inorganic. The results of preliminary tests are used to give direction to subsequent testing procedures which are used for further classification, ultimately into reactivity groups. The scheme is organized in a manner such that materials with high reactivity or unusual hazards are identified early in the testing sequence. In some cases, information gained in the early stages of testing can be used to classify the material and eliminate the need for further testing, or can provide cautions to be applied in subsequent testing activities (i.e., explosive hazard).

The sequence in which test procedures are carried out is shown schematically in Figure 1. The testing sequence begins with a visual examination of the waste material to classify it as a solid, sludge, slurry, or liquid. This examination may give a strong indication of its identity (i.e., metal).

Depending upon the phase of the waste material, preliminary testing is initiated. If the waste is a liquid, slurry, or sludge, PS 1 is carried out first. The rationale for beginning with PS 1 is that the chance for extreme hazards due to acidity and/or redox potential may be greater for liquids than for solids and these hazards are most easily identified. If the material is found to be strongly acidic and/or oxidative, the need for further testing is virtually eliminated (strong acids and oxidizing agents are incompatible with most other classes of wastes).

The test procedure for liquids continues with solution-reactivity tests and flame tests to determine the material's solubility/reactivity characteristics and to identify the waste as organic or inorganic. For organics, functionality tests (PS's 4 and 5) are performed to classify the waste into specific RGN's. For inorganics, PS 6 is conducted to identify specific RGN's.

For solids, the flame test (PS 3) is carried out first, followed by the solution-reactivity tests (PS 2). This sequence is followed to identify explosive and unusual reactivity hazards (i.e., sulfide and cyanide) early in the testing sequence. From PS's 1 and 2, it can be determined if the waste is organic or inorganic. For organics, PS's 4 and 5 tests are performed to categorize the waste into specific RGN's. Inorganics are classified using PS 6.

Procedure Sets

A number of test procedures are employed in the course of hazardous waste compatibility testing. For the sake of organization these have been broken into "procedure sets" which are discussed in detail in the following paragraphs.

PS 1 -- pH and Redox Tests

Early in the testing sequence, pH, oxidation, and reduction tests are performed on a waste material or its aqueous solution by means of test papers. These tests identify some of the most reactive of the RGN's (those with the most

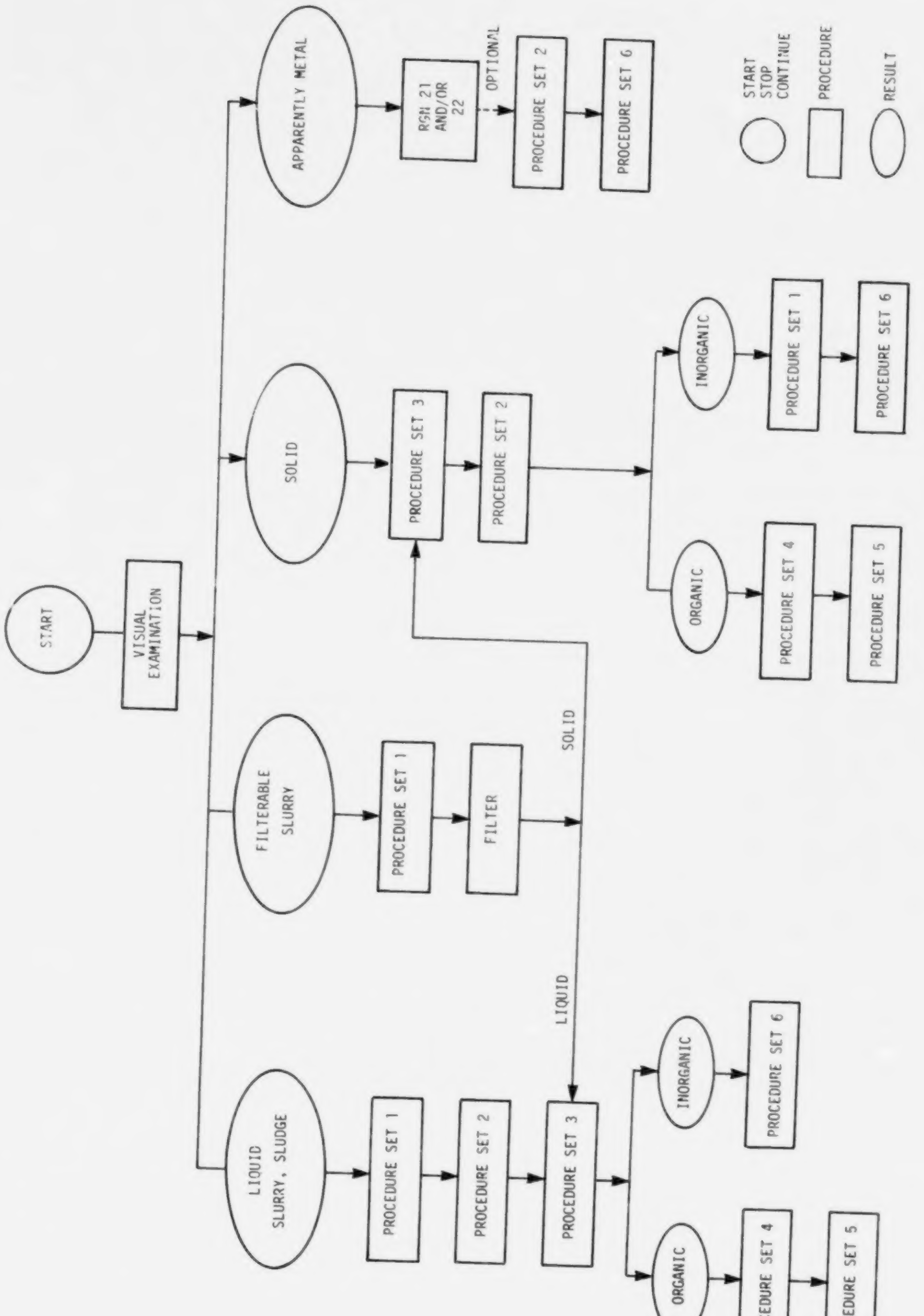
START
VISUAL EXAMINATION
LIQUID SLURRY, SLUDGE
FILTERABLE SLURRY
SOLID
APPARENTLY METAL
PROCEDURE SET 1
PROCEDURE SET 2
PROCEDURE SET 3
FILTER
SOLID
LIQUID
RGN 21 AND/OR 22
OPTIONAL
ORGANIC
INORGANIC
PROCEDURE SET 4
PROCEDURE SET 5
PROCEDURE SET 6
START STOP CONTINUE
PROCEDURE
RESULT

Figure 1. Sequence of procedure sets.

limited compatibility characteristics). Specific RGN's identified are as follows:

- RGN 1 -- Nonoxidizing mineral acids
- RGN 2 -- Oxidizing mineral acids
- RGN 3 -- Organic acids
- RGN 10 -- Caustics
- RGN 104 -- Strong oxidizing agents
- RGN 105 -- Strong reducing agents

PS 1 is shown in Figure 2. It should be noted that classification into RGN's 1, 2, or 104 virtually eliminates the need for further testing since these RGN's are incompatible with most wastes. In addition, classification into RGN's 10 and 104 or 10 and 105 has similar consequences.

PS 2 -- Solution-Reactivity and Special Functionality Tests

This set of test procedures is conducted to determine the reactivity of the waste material with water, acids, and bases, and the solubility of the waste material in aqueous acid, base, and four organic solvents. PS 2 is shown in Figure 3. The first procedure is the treatment of the waste material with water. At this point, most water-reactive materials are identified (and further testing is suspended). The solubility of the material in water is noted. Liquids are tested for the presence of water (RGN 106) and all waste materials are tested for sulfide and cyanide (RGN's 33 and 11, respectively). Finally, the material is treated with an aqueous base, a series of acids, and four solvents. The following RGN's are determined in PS 2:

- RGN 11 -- Cyanides
- RGN 33 -- Inorganic sulfides
- RGN 106 -- Mixtures contaning water
- RGN 107 -- Water-reactive substances

In addition, clues are given regarding the gross identity (reactive, inert, organic, inorganic) of the waste material.

PS 3 -- Flame Tests

Observation of the behavior of a material upon ignition can provide a great deal of insight regarding its composition. Results (observations) upon ignition are characterized by one of the following descriptions:

- Burns violently
- Burns (with or without smoke)
- Produces a colored flame, but does not burn
- Melts but does not burn
- Evaporates or sublimes but does not burn

Figure 4 shows the classification observations. While these observations are somewhat subjective, after the training period by an experienced chemist most observers will be able to make a distinction between organics, inorganics, and free metals using the flame test. RGN 107 (explosive) is determined directly by means of the flame test.

PS 4 -- Ferrox and Sodium Fusion

The classification of a material as primarily organic or inorganic is made in PS's 2 or 3. PS 4 is conducted if it is determined that the material is organic, and provides elemental analysis information. The flow diagram for PS 4 is shown in Figure 5.

This procedure set consists primarily of two tests: sodium fusion with specific tests for nitrogen, sulfur, phosphorus, and halogen (x); and the ferrox test to identify organic materials containing oxygen. In addition, specific optional tests are included to differentiate between classes of hydrocarbons.

The waste material is first subjected to fusion with sodium metal. The metal is thus decomposed, and heteroatoms form

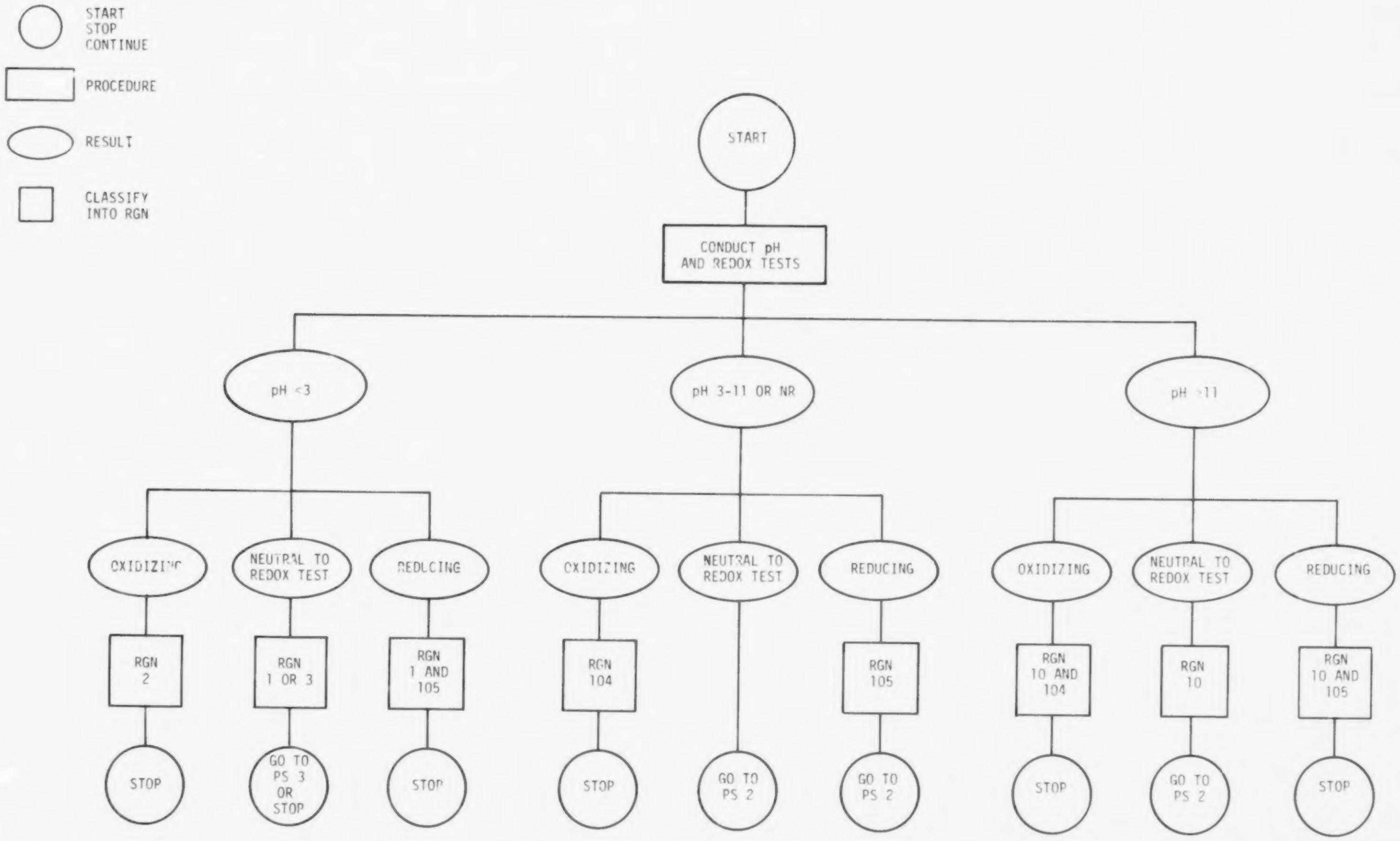
START
STOP
CONTINUE
PROCEDURE
RESULT
CLASSIFY
INTO RGN
START
CONDUCT pH
AND REDOX TESTS
pH <3
pH 3-11 OR NR
pH >11
OXIDIZING
NEUTRAL TO
REDOX TEST
REDUCING
RGN
2
RGN
1 OR 3
RGN
1 AND
105
STOP
GO TO
PS 3
OR
STOP
STOP
OXIDIZING
NEUTRAL TO
REDOX TEST
REDUCING
RGN
104
RGN
105
STOP
GO TO
PS 2
GO TO
PS 2
OXIDIZING
NEUTRAL TO
REDOX TEST
REDUCING
RGN
10 AND
104
RGN
10
RGN
10 AND
105
STOP
GO TO
PS 2
STOP

Figure 2. Procedure set 1 -- pH and redox tests.

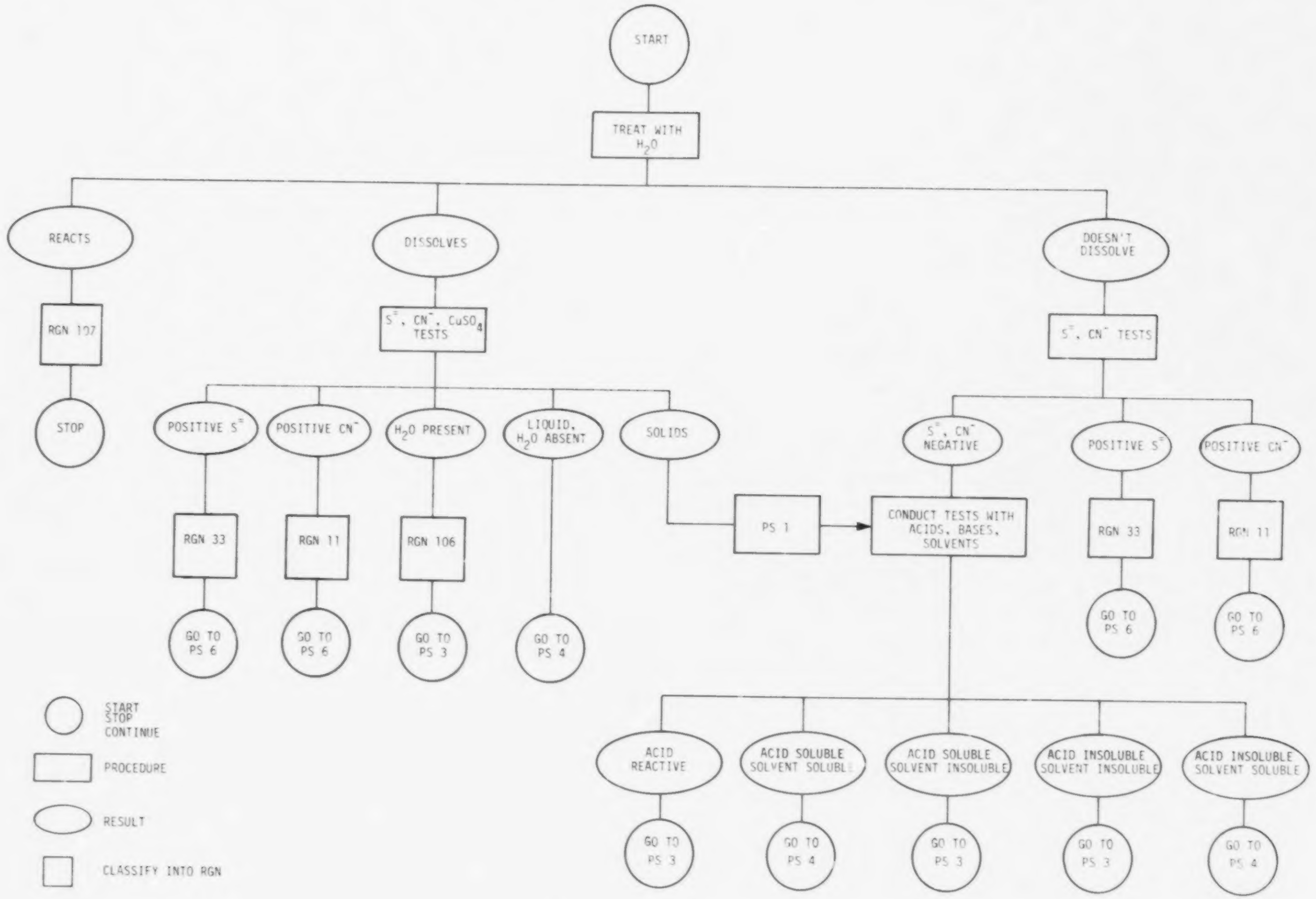
START
TREAT WITH H_2O
REACTS
RGN 107
STOP
DISSOLVES
$S^=$, CN^-, $CuSO_4$ TESTS
POSITIVE $S^=$
RGN 33
GO TO PS 6
POSITIVE CN^-
RGN 11
GO TO PS 6
H_2O PRESENT
RGN 106
GO TO PS 3
LIQUID, H_2O ABSENT
GO TO PS 4
SOLIDS
PS 1
DOESN'T DISSOLVE
$S^=$, CN^- TESTS
$S^=$, CN^- NEGATIVE
CONDUCT TESTS WITH ACIDS, BASES, SOLVENTS
POSITIVE $S^=$
RGN 33
GO TO PS 6
POSITIVE CN^-
RGN 11
GO TO PS 6
ACID REACTIVE
GO TO PS 3
ACID SOLUBLE SOLVENT SOLUBLE
GO TO PS 4
ACID SOLUBLE SOLVENT INSOLUBLE
GO TO PS 3
ACID INSOLUBLE SOLVENT INSOLUBLE
GO TO PS 3
ACID INSOLUBLE SOLVENT SOLUBLE
GO TO PS 4
START STOP CONTINUE
PROCEDURE
RESULT
CLASSIFY INTO RGN

Figure 3. Procedure set 2 -- solution/reactivity and special functionality tests.

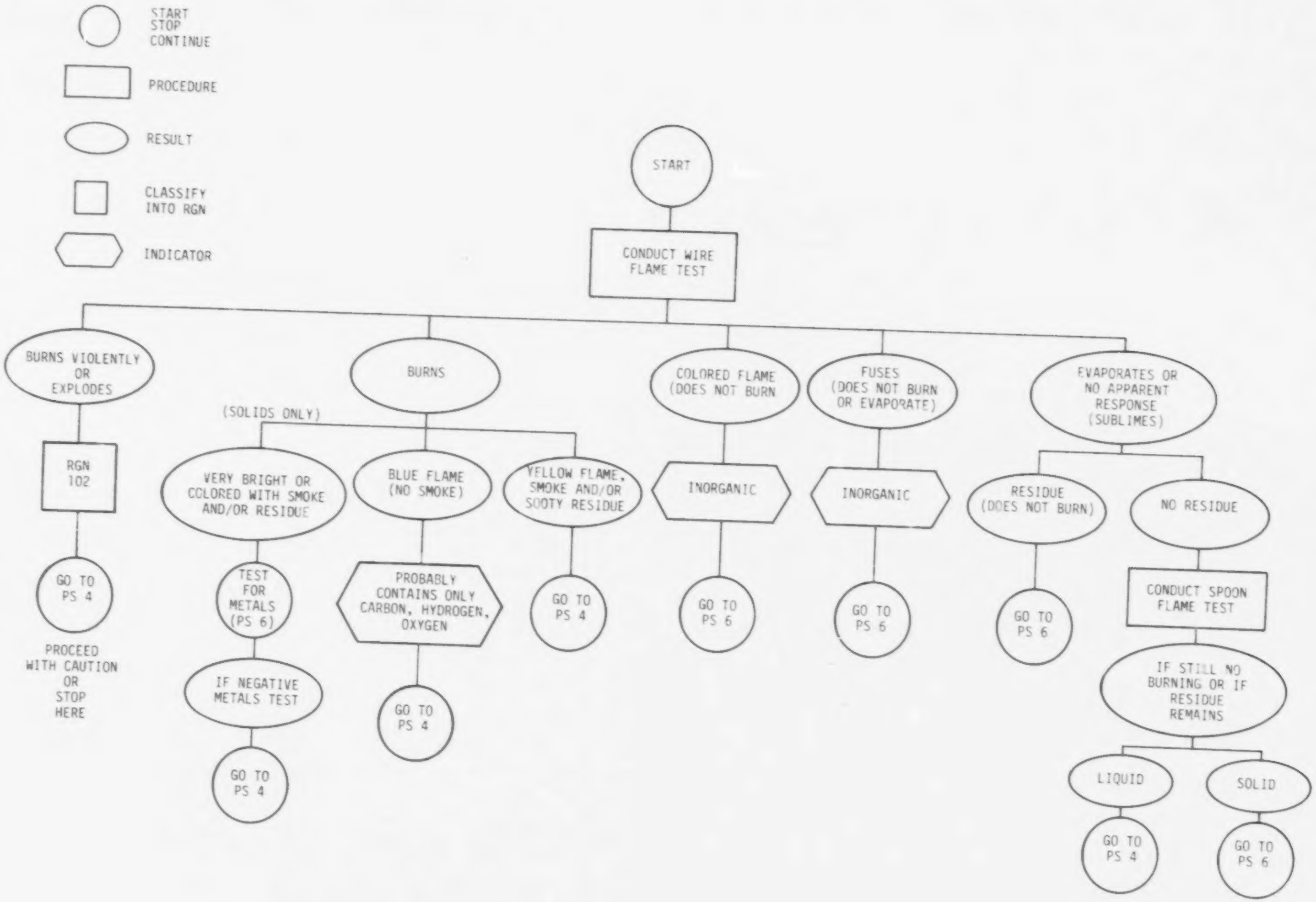
START
STOP
CONTINUE
PROCEDURE
RESULT
CLASSIFY
INTO RGN
INDICATOR
START
CONDUCT WIRE FLAME TEST
BURNS VIOLENTLY OR EXPLODES
RGN 102
GO TO PS 4
PROCEED WITH CAUTION OR STOP HERE
BURNS
(SOLIDS ONLY)
VERY BRIGHT OR COLORED WITH SMOKE AND/OR RESIDUE
TEST FOR METALS (PS 6)
IF NEGATIVE METALS TEST
GO TO PS 4
BLUE FLAME (NO SMOKE)
PROBABLY CONTAINS ONLY CARBON, HYDROGEN, OXYGEN
GO TO PS 4
YELLOW FLAME, SMOKE AND/OR SOOTY RESIDUE
GO TO PS 4
COLORED FLAME (DOES NOT BURN
INORGANIC
GO TO PS 6
FUSES (DOES NOT BURN OR EVAPORATE)
INORGANIC
GO TO PS 6
EVAPORATES OR NO APPARENT RESPONSE (SUBLIMES)
RESIDUE (DOES NOT BURN)
GO TO PS 6
NO RESIDUE
CONDUCT SPOON FLAME TEST
IF STILL NO BURNING OR IF RESIDUE REMAINS
LIQUID
GO TO PS 4
SOLID
GO TO PS 6

Figure 4. Procedure set 3 -- flame tests.

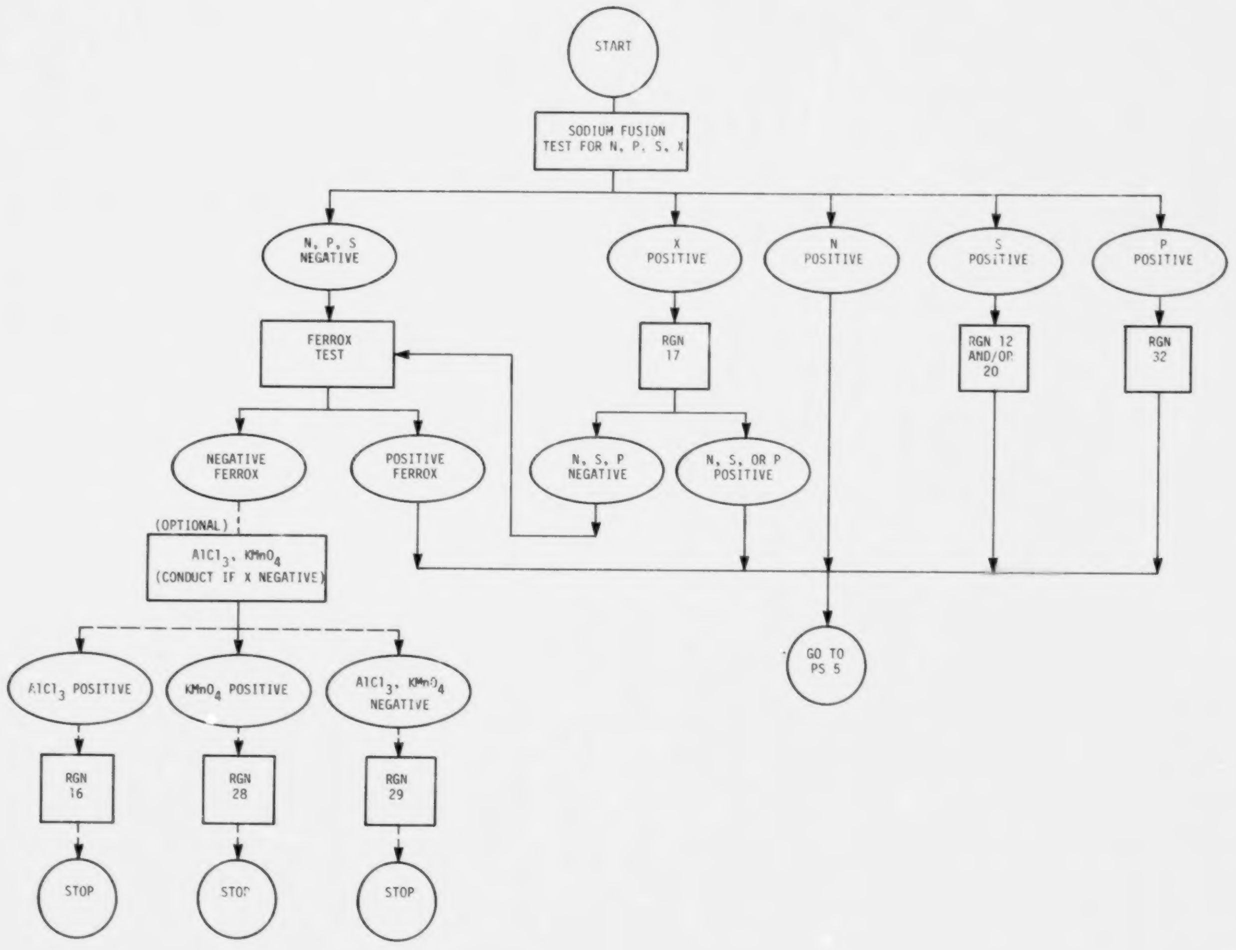
START
SODIUM FUSION TEST FOR N, P, S, X
N, P, S NEGATIVE
X POSITIVE
N POSITIVE
S POSITIVE
P POSITIVE
FERROX TEST
RGN 17
RGN 12 AND/OR 20
RGN 32
NEGATIVE FERROX
POSITIVE FERROX
N, S, P NEGATIVE
N, S, OR P POSITIVE
(OPTIONAL)
$AlCl_3$, $KMnO_4$ (CONDUCT IF X NEGATIVE)
GO TO PS 5
$AlCl_3$ POSITIVE
$KMnO_4$ POSITIVE
$AlCl_3$, $KMnO_4$ NEGATIVE
RGN 16
RGN 28
RGN 29
STOP
STOP
STOP

Figure 5. Procedure set 4 -- ferrox and sodium fusion tests.

sodium sulfide (sulfur), sodium cyanide (nitrogen), sodium phosphate (phosphorus) and/or sodium halide (halogen). Positive tests for sulfur, nitrogen, or phosphorus are followed by appropriate specific functional group tests (PS 6). If tests for sulfur, nitrogen, or phosphorus are negative, the ferrox test is conducted to determine the presence of oxygen. A negative ferrox test indicates the material is a halogenated hydrocarbon (RGN 17- determined by sodium fusion) or a hydrocarbon. Specific optional tests are included to distinquish between aromatics (RGN 16), alkenes (RGN 28), and alkanes (RGN 29). Since compatibility characteristics of RGN's 16, 28, and 29 are similar, it is likely that tests to distinguish these three RGN's are unnecessary.

PS 4 provides for the classification of five RGN's specifically. These are as follows:

- RGN 17 -- halogenated organics
- RGN 32 -- organophosphates, phosphothioates, and phosphodithioates
- RGN 16 -- aromatic hydrocarbons
- RGN 28 -- unsaturated aliphatic hydrocarbons
- RGN 29 -- saturated aliphatic hydrocarbons

Elemental composition information is provided which is utilized in PS 5, discussed in the following paragraphs.

PS 5 -- Organic functionality Tests

Elemental analysis information obtained in PS 4 is used as a starting point for PS 5. This set of procedures includes specific tests for 17 reactivity groups, and is outlined in Figure 6. The PS 5 contains three major parts: tests for functionalities containing sulfur, nitrogen, and/or only oxygen.

If the ferrox test (PS 4) is positive, tests are conducted for functional groups containing oxygen. Three of these (RGN's 3, 30, and 34) are very reactive but information already obtained in PS's 1 and 2 is used in the classification into these RGN's. Other reactivity groups containing only oxygen (RGN's 4, 5, 13, 14, 19, and 31) are less reactive and have similar compatibility characteristics. Separate optional tests are provided for determining the presence of these RGN's, but they may be eliminated and materials with positive ferrox test placed into a composite group representing all of these RGN's.

If the sodium fusion results indicate the presence of nitrogen in the waste material, tests for functional groups containing nitrogen are conducted. Like the RGN's containing only oxygen, three RGN's (8, 9, and 18) are much more reactive than the others. Tests are therefore conducted for RGN's 8, 9 and 18 and optional tests for RGN's 6, 7, 26, and 27 are provided.

If sulfur is present (from the sodium fusion), RGN's 12 and/or 20 are indicated. These can be distinguished by individual (optional) tests. The compatibility characteristics of these two RGN's are similar, however, and conducting tests to distinguish them is probably not necessary.

In summary, 17 RGN's are determined in PS 5:

- Oxygen functional groups
  - RGN 3 -- Organic acids
  - RGN 4 -- Alcohols and glycols
  - RGN 5 -- Aldehydes
  - RGN 13 -- Esters
  - RGN 14 -- Ethers
  - RGN 19 -- Ketones
  - RGN 31 -- Phenols and cresols
  - RGN 34 -- Epoxides
  - RGN 30 -- Peroxides
- Nitrogen functional groups
  - RGN 6 -- Amides
  - RGN 7 -- Amines

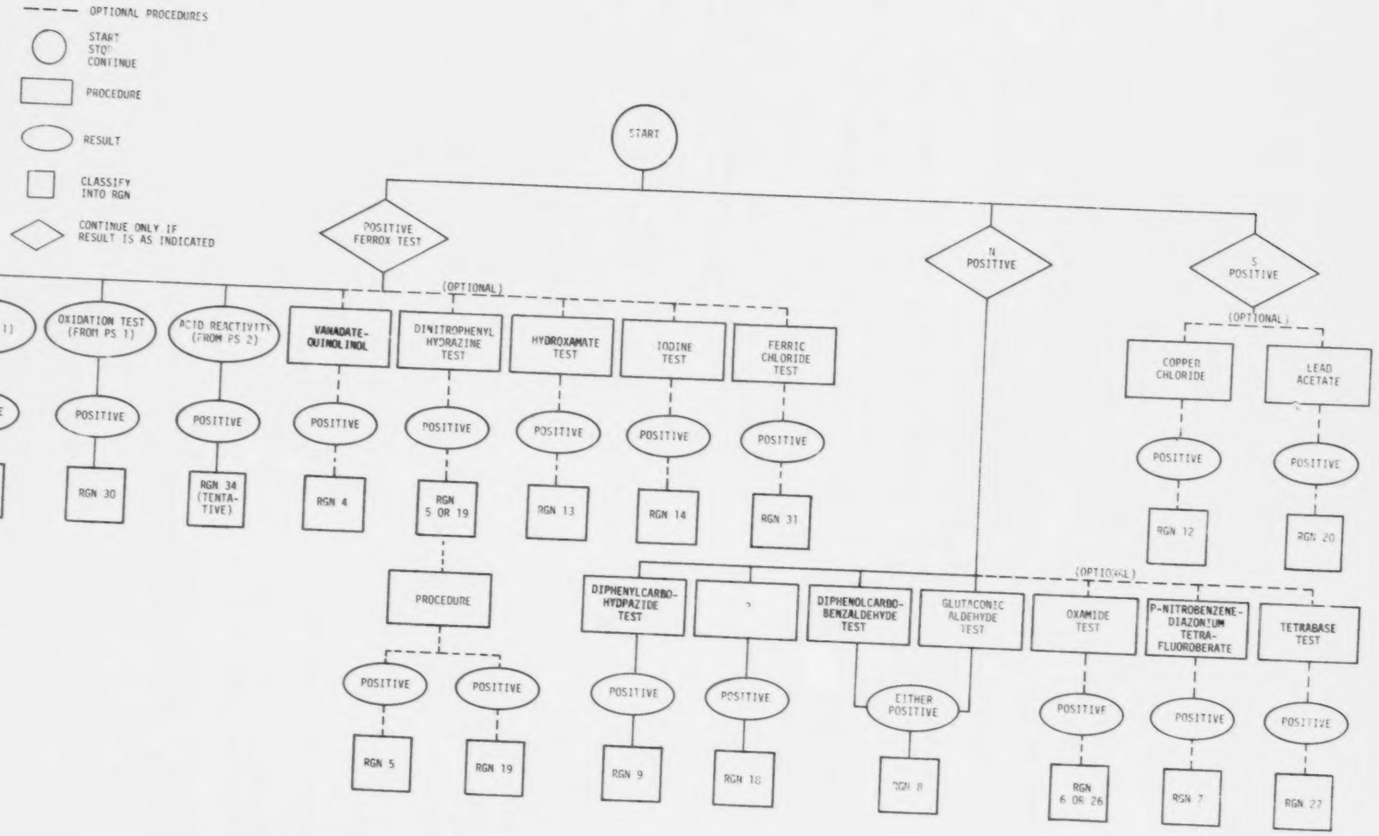
OPTIONAL PROCEDURES
START
STOP
CONTINUE
PROCEDURE
RESULT
CLASSIFY INTO RGN
CONTINUE ONLY IF RESULT IS AS INDICATED
START
POSITIVE FERROX TEST
N POSITIVE
S POSITIVE
(OPTIONAL)
pH <5 (FROM PS 1)
OXIDATION TEST (FROM PS 1)
ACID REACTIVITY (FROM PS 2)
VANADATE-QUINOLINOL
DINITROPHENYL HYDRAZINE TEST
HYDROXAMATE TEST
IODINE TEST
FERRIC CHLORIDE TEST
POSITIVE
RGN 3
RGN 30
RGN 34 (TENTATIVE)
RGN 4
RGN 5 OR 19
RGN 13
RGN 14
RGN 31
PROCEDURE
RGN 5
RGN 19
(OPTIONAL)
COPPER CHLORIDE
LEAD ACETATE
RGN 12
RGN 20
(OPTIONAL)
DIPHENYLCARBO-HYDPAZIDE TEST
?
DIPHENOLCARBO-BENZALDEHYDE TEST
GLUTACONIC ALDEHYDE TEST
OXAMIDE TEST
P-NITROBENZENE-DIAZONIUM TETRA-FLUOROBERATE
TETRABASE TEST
EITHER POSITIVE
RGN 9
RGN 18
RGN 8
RGN 6 OR 26
RGN 7
RGN 27

Figure 6. Procedure set 5 -- organic functionality tests.

RGN 8 -- Azo compounds, diazo compounds, and hydrazines

RGN 9 -- Carbamates

RGN 18 -- Isocyanates (no test)

RGN 26 -- Nitriles

RGN 27 -- Organic nitro compounds

- Sulfur functional groups

  RGN 12 -- Dithiocarbamates

  RGN 20 -- Mercaptans and other organic sulfides

PS 6 -- Inorganic Functionality Tests

PS 6 includes tests for metals and other inorganic species not identified in PS's 1 and 2. These tests are outlined in Figure 7.

Solids are tested for metals using phosphomolybdic acid. The form of the metal (sheets, powder, etc.) is determined by inspection. Alkali metals are determined by their water reactivity. If the material is not an elemental metal it is dissolved (using HNO_3 if necessary). This solution (or liquid waste) is tested for the presence of heavy metal compounds (RGN 24) and for fluorides (RGN 15).

The reactivity groups determined in PS 6 are the following:

- RGN 15 -- Inorganic fluorides
- RGN 21 -- Elemental alkali and alkaline earth metals
- RGN 22 -- Elemental metals in the form of powders, vapors, or sponges
- RGN 23 -- Elemental metals in the form of sheets, rods, mouldings, drops, etc.
- RGN 24 -- Toxic metals and metal compounds

It should be noted that a test has not been identified for RGN 25, nitrides, but these compounds fit into the explosives class (RGN 102), determined in PS 2.

Determination of Compatibility

After completion of the appropriate test procedures, a waste material is classified into one or more reactivity groups, based upon the test results. At this point, the compatibility chart (1) is consulted to determine the potential effects of mixing with wastes of other classes. In cases where compatibility is indicated, wastes are mixed on a small scale as described in the following paragraphs.

Construction of a Test Mixing Device

Compatibility between binary pairs of waste materials must be demonstrated by mixing on a small scale even if compatibility is indicated by the compatibility chart (1). Devices have been reported (6, 7) which are used to evaluate the effects of mixing two materials. One such device (6) employs a modified Dewar flask and another (7) employs a Parr minireactor. The requirements of such a device are the following:

- A means to introduce materials into a closed container
- A stirring device
- Pressure and temperature sensing devices

A simple apparatus has been constructed from readily available laboratory glassware. It is made from a large side-arm test tube, fitted with stirring and sensing devices. The stirrer is a mechanical stirring shaft that can be turned by hand. A digital thermometer and a bubbler to detect temperature and pressure changes are attached. A diagram of the device is shown in Figure 8.

The test device shown in Figure 8 has the advantages of portability and ease of operation over those described earlier. In addition, unusual effects of mixing can be observed through the transparent container.

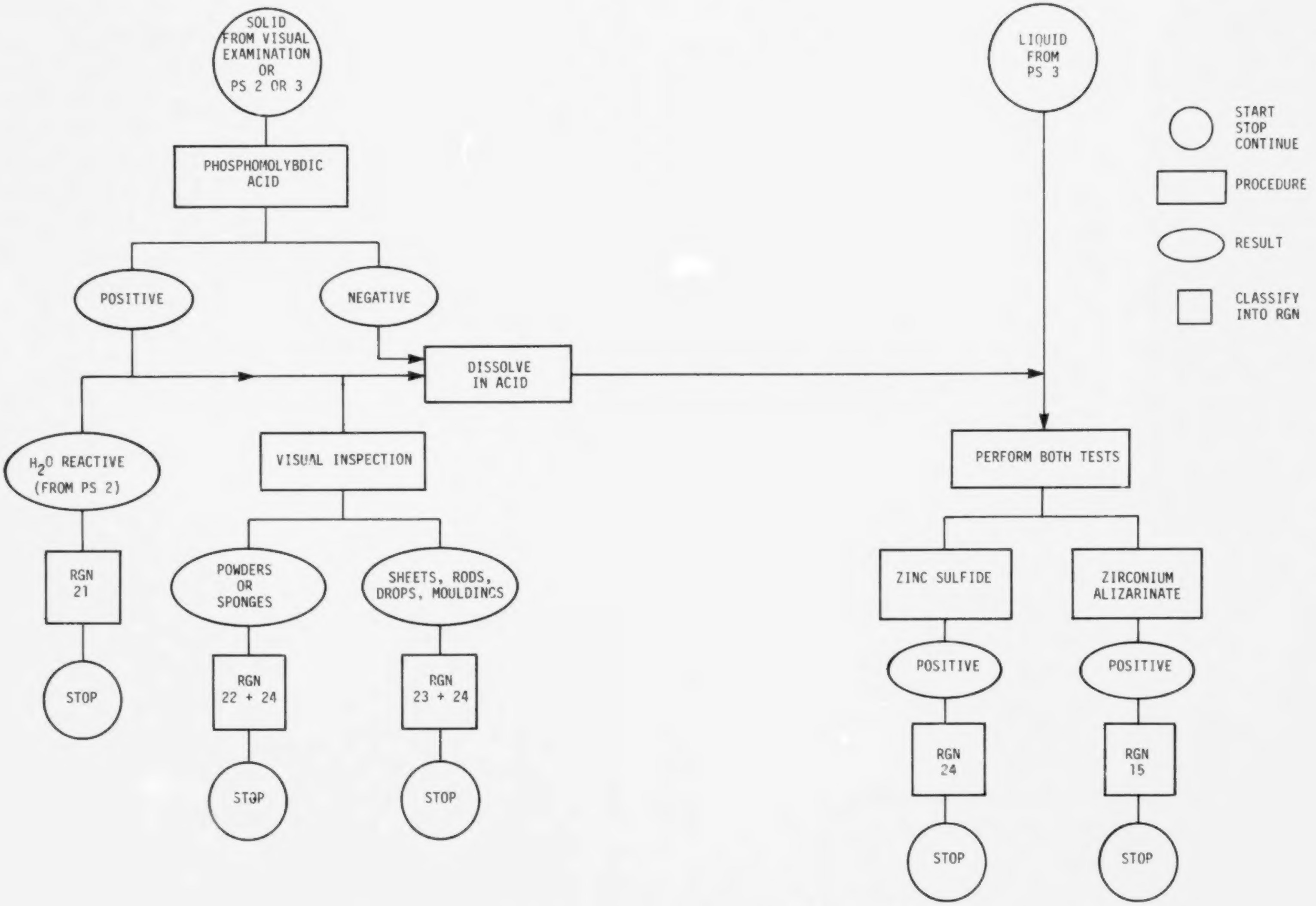
SOLID FROM VISUAL EXAMINATION OR PS 2 OR 3
PHOSPHOMOLYBDIC ACID
POSITIVE
NEGATIVE
DISSOLVE IN ACID
H_2O REACTIVE (FROM PS 2)
VISUAL INSPECTION
RGN 21
STOP
POWDERS OR SPONGES
SHEETS, RODS, DROPS, MOULDINGS
RGN 22 + 24
RGN 23 + 24
STOP
STOP
LIQUID FROM PS 3
PERFORM BOTH TESTS
ZINC SULFIDE
ZIRCONIUM ALIZARINATE
POSITIVE
POSITIVE
RGN 24
RGN 15
STOP
STOP
START STOP CONTINUE
PROCEDURE
RESULT
CLASSIFY INTO RGN

Figure 7. Procedure set 6 -- inorganic functionality tests.

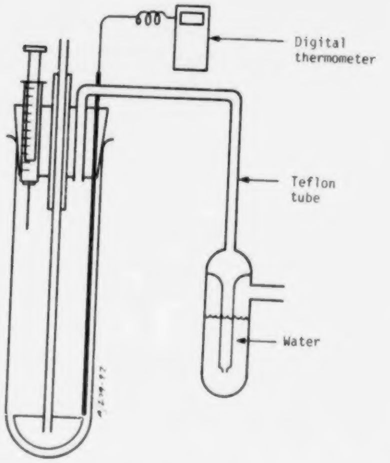

Figure 8. Apparatus for test mixing hazardous wastes.

EXPERIMENTAL RESULTS

Tests have been performed on all of the selected compounds listed in Table 1 for pH flame, oxidation, reduction and solution-reactivity (corresponding to PS's 1 through 3). A generalized summary of pH, oxidation, and reduction test results is presented in Table 3. A generalized summary of solution-reactivity test results is presented in Table 4. All results represent those expected, except that certain oxidizing agents bleach colored test papers.

Sodium fusion and ferrox tests have been performed for organic test compounds listed in Table 2. Results for all compounds are as expected, based upon the molecular structure of compounds involved. The sodium fusion and ferrox results are summarized in Table 5. It should be noted that excess sulfur tends to interfere with tests for phosphorus and halogen (due to precipitation of metallic sulfides). This interference was removed by acidifying the fusion extract and boiling briefly to expel hydrogen sulfide. In two cases, namely, aminothiazole and mercaptobenzothiazole, tests for cyanide (nitrogen) gave weak positive responses, but a positive thiocyanate test was produced. A footnote was therefore added to the test procedure to test for thiocyanate in the presence of sulfur.

fusion extract and boiling briefly to expel

Results of functionality tests are presented in Table 5. In all, over 450 individual tests were performed with sixteen false positive observations and six false negative results.

CONCLUSION

A series of published analytical test procedures have been compiled for use in categorizing hazardous waste into reactivity groups, using a set of flowcharts. To date, testing of 57 compounds using test procedures in all of the six procedure sets has been completed, with no significant anomalous results. In addition, several mixtures and "blind" samples have been tested. Demonstration of the applicability of the test scheme to real waste samples is to be completed.

Specific test procedures have been identified for all but four reactivity groups listed in Reference 1. These four reactivity groups are the following:

- RGN 18 Isocyanates
- RGN 25 Nitrides
- RGN 34 Epoxides
- RGN 103 Polymerizable compounds

A continuing effort is being made to identify appropriate functional group tests for these four classes of materials.

Two concerns have been expressed regarding the applicability of these test procedures to field operations at hazardous waste sites. The first concern is the safety of personnel conducting the tests. Safety is maximized by utilizing very small quantities of test materials, and by the use of appropriate protective clothing and devices (i.e., safety shield). Prior to conducting the sodium fusion tests, concern about its safety was expressed. It was

TABLE 3. GENERAL SUMMARY OF FLAME, pH, REDOX TEST RESULTS

General compound class	Flame test	pH	Oxidation (KI-starch)	Reduction (methylene blue)
Metals and metal salts	Colored flames; Cd, Cr, Pb, Ba, Na burn brightly, others do not burn; CrO_3 burns very brightly	CrO_3 - low pH Na and Ba react to give pH ~11	CrO_3 - positive test $Ca(OCl)_2$ $Ca(OCl)_2$ positive test	Active metals give NR $Ca(OCl)_2$ bleaches paper
Acids -- inorganic	Generally do not burn; fluoboric acid bright green; most give yellow (Na) flame	pH ≈1		NR
Aliphatic hydrocarbons and oxygen CPDs	Benzoyl peroxide burns violently, others have blue flames -- no smoke -- no residue; alkenes yellow flames	No response acids pH 3-5	Benzoyl peroxide gives positive response, others NR	NR
Aromatic hydrocarbons	Yellow flames, black smoke	NR	NR	NR
Organosulfur, phosphorus, and nitrogen compounds	Burns with white-yellow smoke	NR Amino Cpds pH ≈10	NR	NR
Explosives (picrates)	Burns violently ("sparkles")	pH ≈5 for picric acid	NR	NR

NR -- no observable response

TABLE 4. GENERAL SUMMARY OF SOLUTION-REACTIVITY TEST RESULTS

Compound class	H_2O	HCl	HNO_3	H_2SO_4	NaOH	Polar solvents MeOH, acetone	Nonpolar solvents hexane, toluene
Hydrocarbons	NR	NR	NR	NR	NR	DISS, acetone NR, MeOH	DISS (except polypropylene)
Esters, ethers, acids, aldehydes and ketones	NR	DISS	DISS (color change)	DISS (turn brown)	NR or DISS	DISS or NR	DISS or NR
Nitro compounds and picrates	DISS	DISS	DISS	DISS	DISS, red color	DISS or NR	DISS or NR
Amines	NR or DISS	DISS	DISS (discolored)	NR or darkens	NR	DISS or NR	DISS or NR
Isocyanates, nitriles	NR	NR	Vigorous RXN, brown fumes	NR or darkens	NR	DISS or NR	DISS or NR
Mercaptans	NR	NR or DISS	Brown fumes	NR or darkens	DISS or NR	DISS or NR	DISS or NR
P-compounds	NR	NR or DISS	Brown fumes	Darkens	DISS or NR	DISS or NR	DISS or NR
Epoxides	DISS, gas	DISS, gas	Violent spattering	Vigorous RXN	DISS or NR	DISS or NR	DISS or NR
Reactive olefins (polymerizable)	NR	DISS	DISS or NR	DISS or darkens	NR	DISS or NR	DISS or NR
Inorganic acids	DISS	DISS	DISS	DISS + fumes	DISS	DISS or NR	NR
Metallic elements	NR except Na and Ba (gas evol.)	Slow gas evolution	Gas, brown fumes (some metals violent reaction)	Slow RXN (gas evolution)	NR except Na and Ba (gas evol.)	NR except Na and Ba (gas evol.)	NR
Oxidizing agents	DISS	DISS $Ca(OCl)_2$, fumes	DISS $Ca(OCl)_2$, fumes	DISS $Ca(OCl)_2$, fumes	DISS	CrO_3, violent $Ca(OCl)_2$, NR	NR
Salts and oxides	DISS or NR	DISS, fumes or NR	DISS, fumes or NR	DISS, fumes or NR	DISS or NR	NR	NR

NR = No observable response
DISS = Dissolves

TABLE 5. SUMMARY OF FUNCTIONALITY TEST RESULTS

Test name	Parameter	Tests conducted	Positive results expected	False positive results	False negative results
Sodium fusion					
Cyanide/thiocyanate	Organic nitrogen cpds	40	18	0	0
Sulfide	Organic sulfur cpds	40	8	0	0
Phosphate	Organic phosphorus cpds	40	2	0	0
Halide	Organic halogen cpds	40	2	0	0
Ferrox test	Organic oxygen cpds	40	10	1	1
pH	Acids (organic)	40	3	2	0
Vanadium oxinate	Alcohols	40	3	0	0
Dinitrophenylhydrazine	Aldehydes and ketones	40	4	0	0
Schiff's test	Aldehydes	40	1	0	0
Hydroxamate	Esters	40	5	0	0
Iodine test	Ethers	40	8	7	0
Ferric chloride	Phenols	40	2	2	1
Potasium iodide-starch	Peroxides	40	2	0	0
Oxamide	Amides and/or nitriles	22	5	0	0
Dinitrochlorobenzene	Amines	22	4	1	1
Dimethylaminobenzaldehyde	Azo compounds	22	1	0	0
Glutaconic aldehyde	Hydrazines	23	1	0	0
Diphenylcarbohydrazide	Carbamates	22	1	3	3
Tetrabase fusion	Nitro compounds	22	4	0	0
Copper chloride	Dithiocarbamates	22	2	0	0
Lead acetate	Mercaptans and other organic sulfides	22	3	0	0
Baeyer's test	Unsaturated hydrocarbons	13	4	0	0
Friedel-Crafts test	Aromatic hydrocarbons	3	3	0	0
Zirconium alizarinate	Inorganic fluorides	10	5	0	0
Phosphomolybdic acid	Elemental metals	16	10	0	0
Sulfide	Heavy metal compounds	16	16	0	0
Total		755	--	16	6

found to be satisfactory, however, even with heat sensitive compounds such as picric acid and benzoyl peroxide.

The second concern is the length of time required to perform enough tests to completely classify a waste material. In response to this concern, test procedures for certain reactivity groups will be labeled as optional, based on similarity of compatibility characteristics between key reactivity groups. As an example, for the purpose of compatibility testing, it is probably not necessary to distinguish between aliphatic and aromatic hydrocarbons. Even if optional tests are included, it is anticipated that a complete set of tests (sufficient for categorization) can be performed on a waste material in 1 to 2 hours, as a worst case. Mixing tests are expected to take 15 minutes maximum. By using the instruction manual being written as part of the test kit, it is anticipated that analysts without a significant chemistry background can learn to use the test procedures safely and effectively with minimal training.

ACKNOWLEDGMENTS

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DEMONSTRATION OF THE BLOCK DISPLACEMENT METHOD AT WHITEHOUSE, FLORIDA

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Waltham, Massachusetts 02254

ABSTRACT

Foster-Miller, Inc. has conducted a demonstration of a new remedial action technique for isolating chemical waste sites. This demonstration was carried out adjacent to the Whitehouse Oil Pits in Whitehouse, Florida, and a report of preliminary conclusions was presented before the National Conference on Management of Uncontrolled Hazardous Waste Sites in Washington, DC in November, 1982. This paper presents updated data interpretations and conclusions drawn from more detailed data analysis.

The Block Displacement Method (BDM) is intended to place a low permeability barrier around and under a large block of earth by means of a combination of drilling, notching, fracturing, and slurry injection culminating in the upward displacement of the entire earth mass. There are two separate processes: one for perimeter barrier construction, the second for bottom barrier construction. These two processes impact each other and the nature and sequence of their application is geologic-dependent.

In demonstrating the process at Whitehouse, Florida, horizontal fractures were extended at a depth of 25 ft from seven injection holes within a 60 ft diam block. These fractures coalesced to form a separation extending to a semi-fractured perimeter.

The block was then displaced upward as much as 12 in. by injection of approximately 2,000 ft^3 of bentonite slurry. Upward displacement was monitored by standard survey techniques during the injection phase. Following displacement completion core drilling and geophysical surveys were conducted to verify the integrity of the bottom barrier.

INTRODUCTION

The Block Displacement Method (BDM) is a new method proposed for complete in situ isolation of contaminated earth, and in so doing, placing an "impermeable" barrier at the bottom and sides of the mass. The concept attracted interest at EPA as a potentially cost-effective alternative for remedial, and possibly emergency action. The purpose of the program discussed herein was to develop the technique through a test and demonstration program. The program was configured to demonstrate the feasibility of the BDM and to obtain further data for its development and future implementation. A review of the preliminary project conclusions was presented before the National Conference on Management of Uncontrolled Hazardous Waste Sites, in Washington, D.C., in November, 1982. This paper presents an updated analysis of the results of the field work, along with our recommendations for further concept development.

Actual costs of the design and construction associated with the conduct of this project have not been segregated as this is being written; resources expended within the various phases of this work will be reported at the Symposium presentation.

The BDM is of particular value in strata where unweathered bedrock or other impermeable continuum is not sufficiently near the surface for a perimeter barrier alone to act as an isolator. The barrier material should be compatible with in situ soil, groundwater, and leachate conditions. The barrier is formed by pumping slurry composed of local or imported soil, bentonite and water, into a series of notched injection holes. The resulting barrier completely encapsulates the earth mass or block. A typical BDM barrier is shown in Figure 1.

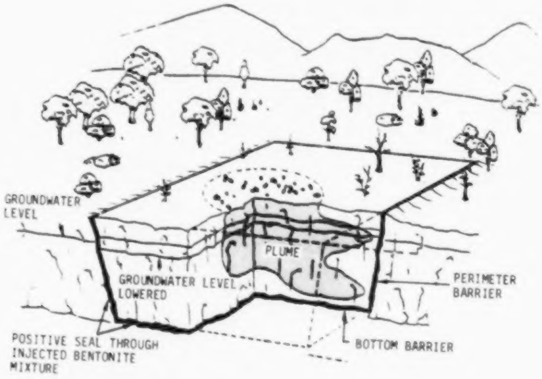

GROUNDWATER LEVEL
PLUME
GROUNDWATER LEVEL LOWERED
PERIMETER BARRIER
POSITIVE SEAL THROUGH INJECTED BENTONITE MIXTURE
BOTTOM BARRIER

Figure 1. BDM Barrier in Place

A perimeter separation is first developed and then surcharged (if necessary) to ensure a favorable horizontal stress field in the formation (Figure 2).

The scale of the "block" for the test and demonstration program was selected to be 60 ft in diameter and 23 ft deep. These dimensions were considered to be large enough to represent significant geologic features and behaviors, yet small enough to be managed within the resources available from EPA's Office of Research and Development. The test site was chosen to be in uncontaminated ground adjacent to a contaminated site, thus facilitating future application at that particular waste site. Based on a review of the initial list of 114 Superfund designated sites, and on an elimination process based on weather, geology, litigation status, and state interest, the Whitehouse site near Jacksonville, Florida was selected for the BDM demonstration.

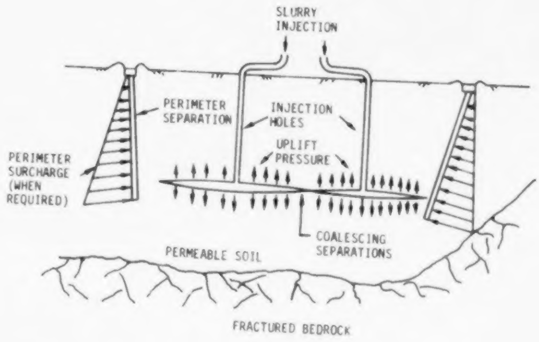

SLURRY INJECTION
PERIMETER SEPARATION
INJECTION HOLES
UPLIFT PRESSURE
PERIMETER SURCHARGE (WHEN REQUIRED)
COALESCING SEPARATIONS
PERMEABLE SOIL
FRACTURED BEDROCK

Figure 2. Creating Separation to Induce Displacement

The Whitehouse site is relatively flat terrain composed of marine sediments of silty sand in excess of 100 ft overlaying limestone bedrock. The silty sand was judged to be sufficiently stratified, see Figure 3, to complement the block displacement process.

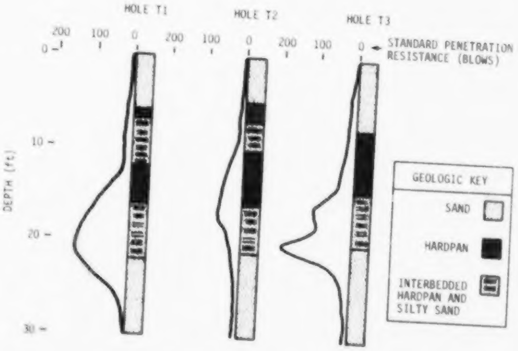


Figure 3. BDM Demonstration Geology

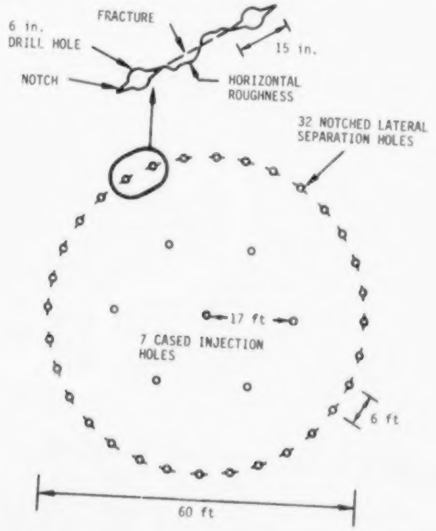
Groundwater level in the area varies from 2 to 5 ft of depth and local drillers indicated that a thick hard pan layer existed at a depth of approximately 20 ft.

FIELD OPERATIONS

The field operation involved three distinct operations:

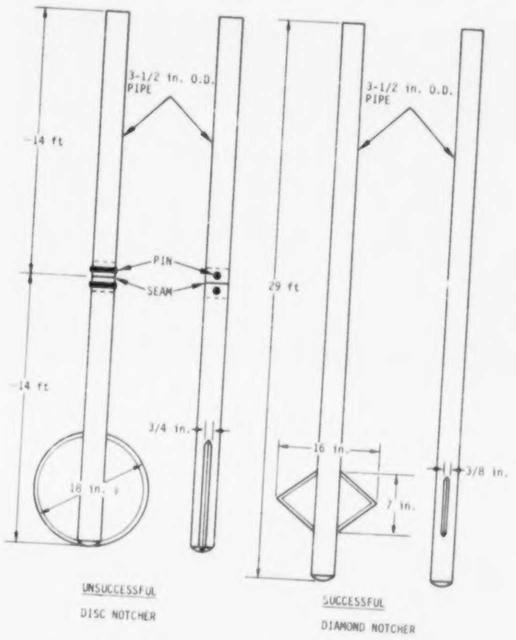
- An explosive blast in three adjacent test holes to determine perimeter fracture performance.
- Preparation of the block by drilling and notching 32 perimeter and seven slurry injection holes
- Fracturing both bottom and perimeter and lifting the block.

Following trial blasts on three test holes spaced 3 ft and 6 ft apart respectively, a final perimeter pattern of 6 in. diam holes on 6 ft spacing was drilled (Figure 4). These holes were each notched from top to bottom with a 15 in. span notching tool (Figure 5), following tests with three earlier notching tool designs.



6 in. DRILL HOLE
FRACTURE
15 in.
NOTCH
HORIZONTAL ROUGHNESS
32 NOTCHED LATERAL SEPARATION HOLES
17 ft
7 CASED INJECTION HOLES
6 ft
60 ft

Figure 4. BDM Perimeter and Injection Hole Spacing



3-1/2 in. O.D. PIPE
~14 ft
PIN
SEAM
~14 ft
3/4 in.
18 in.
3-1/2 in. O.D. PIPE
29 ft
16 in.
7 in.
3/8 in.
UNSUCCESSFUL
DISC NOTCHER
SUCCESSFUL
DIAMOND NOTCHER

Figure 5. Perimeter Hole Notchers

Seven injection holes were drilled and cased with 25 ft long 6 in. diam PVC tubing which was cemented in place at the base. The casing extended to a depth of 23 ft leaving 2 ft of casing exposed above ground.

Horizontal notches approximately 2 ft in diameter were cut on all seven injection holes using a slurry jet notching tool.

In parallel with bottom notching, an 18 in. diam, 5 ft high concrete forming tube was placed over each drilled and notched perimeter hole and filled with high density slurry, (Figure 6). Upon culmination of injection hole bottom notching all 32 perimeter holes were line loaded with prima cord explosive (50 grains/ft) and blasted simultaneously. Connecting fractures were observed at the surface between adjacent perimeter holes (Figure 7).

BDM system analysis indicated horizontal separation should initiate from the bottom notches at an injection hole pressure of approximately 20 psi. Initial attempts at injection required pressures in excess of

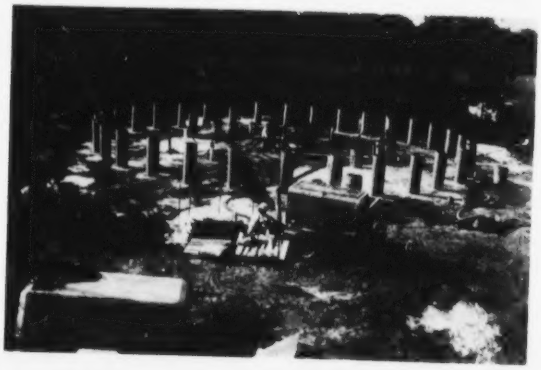


Figure 6. Surcharged Perimeter Holes Ready for Explosive Blast

Figure 7. Surface Fracture Induced by Perimeter Blast

40 psi to induce slurry flow indicating that renotching of each injection hole followed by immediate slurry injection was required.

Bottom notched separation propagation was finally realized by increasing notch diameter to approximately 4 ft using a slurry jet in air medium to cut the formation (Figure 8). Each notching operation was followed by immediate slurry injection to propagate a local separation.

Renotching and local propagation was carried out in all six intermediate injection holes. This procedure was then applied to the central injection hole followed by steady state slurry pumping.

Separation coalescence between injection holes was observed after approximately 500 gallons of slurry was pumped into the central injection hole. Pressure response was documented at intermediate injection hole well heads followed by observance of slurry flow up the perimeter holes at multiple points around the block. Perimeter flow was characterized by small flows from approximately 10 of the concrete forming tubes. During the course of block displacement several of these tubes were replaced with 10 to 20 ft long plugs to impede excessive flows at the perimeter.

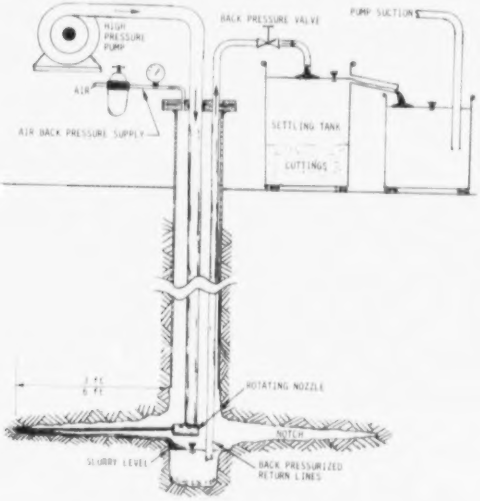


Figure 8. Slurry Jet in Air Notching Operation

Following separation coalescence block displacement was observed over most of the block surface. Block displacement then proceeded over a 2 week period by pumping approximately 2 yd/hr alternately into each injection hole. The resulting upward displacement of the block is shown in Figure 9.

DISCUSSION OF DATA AND RESULTS

Displacement of the block was monitored by recording the change in elevation of 16 fixed rods located as shown in Figure 10. The numbers

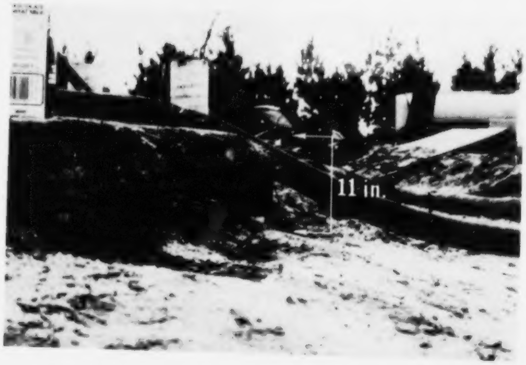


Figure 9. Maximum Upward Displacement at Surface due to Block Lift

in parentheses are the total recorded lift in inches at the corresponding positions on the block. Elevations were read through a surveyor's level located 50 ft outside of the block perimeter. Additional survey points beyond the block boundary were monitored during a portion of the lift operation to verify that no lift was occurring outside of the perimeter. Survey points 0 through 6 correspond to rods located adjacent to (approximately 3 ft from) injection holes. The remaining 9 survey points 3p through 30p correspond to rods located just inside the perimeter. These survey point numbers correspond to the closest perimeter drilled hole numbered progressively from 1 to 32 in a counterclockwise direction.

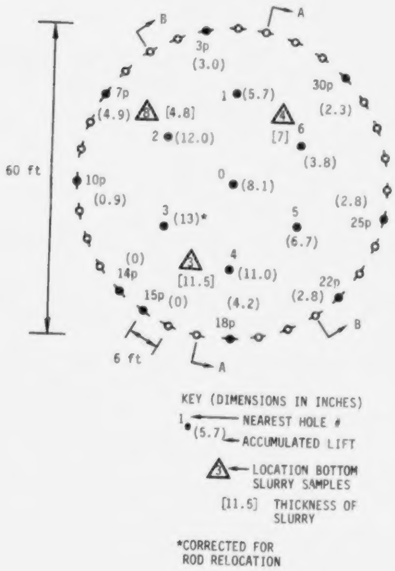

60 ft
6 ft
A
B
3p
(3.0)
1 (5.7)
30p
7p
(4.9)
[4.8]
[7]
6
(2.3)
2 (12.0)
(3.8)
0
(8.1)
10p
(0.9)
3 (13)*
5
(2.8)
25p
(6.7)
(0)
14p
[11.5]
4 (11.0)
22p
15p (0)
(4.2)
(2.8)
18p
KEY (DIMENSIONS IN INCHES)
NEAREST HOLE #
ACCUMULATED LIFT
LOCATION BOTTOM SLURRY SAMPLES
[11.5] THICKNESS OF SLURRY
*CORRECTED FOR ROD RELOCATION

Figure 10. Recorded Block Lift and Verified Seal Thickness

A total of approximately 2000 ft^3 of bentonite slurry was injected during the block lift operation. A daily tabulation of slurry injected during the lift operation was maintained by counting the number of 1-1/2 yd barrels of slurry mixed and verifying this count with a daily bag count of powered bentonite used. A comparison of volume of slurry pumped to volume of block displaced (Figure 11), indicates an initial excess of slurry pumped followed by a consistent correlation once steady state pumping was achieved.

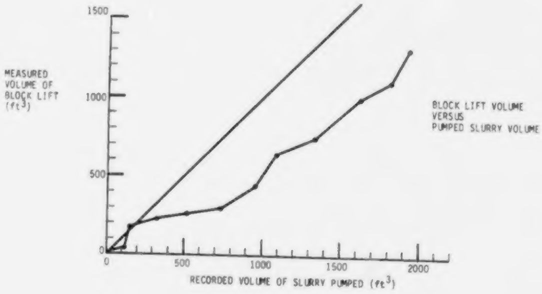


Figure 11. Comparison of Slurry Pumped to Volume Displaced during Block Lift

Data from surface topographic surveys and accumulated daily lift records were combined to give two profiles which inferred the final block position shown in Figure 12. In total, the block was displaced upward in excess of 12 in. at its highest point and tilted approximately 1 deg from horizontal. A crescent-shaped portion of the block outside intermediate injection hole #3, but inside the originally planned block perimeter, was sheared free of the upward-moving block and did not move significantly. The block area near the planned perimeter lagged the main portion of the block by 3 to 6 in. in upward displacement. This lag was present around nearly the entire circumference, except for the stationary crescent.

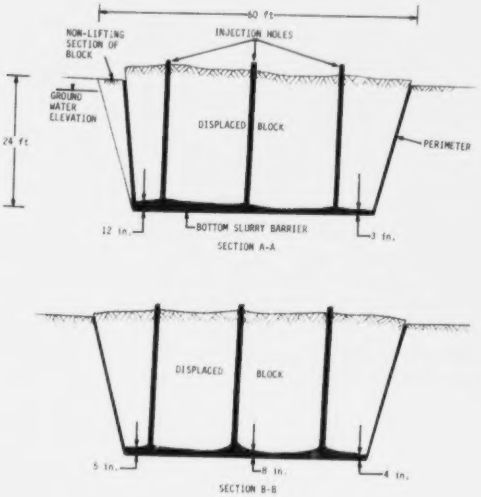

60 ft
NON-LIFTING SECTION OF BLOCK
INJECTION HOLES
GROUND WATER ELEVATION
24 ft
DISPLACED BLOCK
PERIMETER
12 in.
BOTTOM SLURRY BARRIER
3 in.
SECTION A-A
DISPLACED BLOCK
5 in.
8 in.
4 in.
SECTION B-B

Figure 12. Final Block Displacement

The crescent-shaped shear zone, tilting of the block and perimeter displacement lag were all attributed to an incomplete fracturing and freeing of the block around the perimeter. Follow completion of the block lifting operation, 4 to 6 ft deep trenches were excavated through the perimeter and shear zone to try to determine causes of resistance to perimeter displacement.

Tap roots as large as 12 in. in diameter and typically on 6 ft centers were found extending from approximately 5 ft below surface to the upper boundary of the hardpan layer. In addition, perimeter fractures filled with gelled slurry extended down only a few feet before becoming unmapable hairline fractures.

Thin-walled tube soil samples were taken 4 weeks after discontinuation of slurry pumping to determine the integrity of the bottom seal. Obtaining undisturbed soil samples of the soft slurry material bounded by hardpan on top and unconsolidated sand beneath was a difficult task. In eight attempts, three acceptable samples were obtained at the locations shown in Figure 10. Sample No. 8, shown in Figure 13, indicates a well defined boundary of separation between injected clay slurry and the overlaying native sand. Traces of slurry migrated into fractures in the underlaying sand.

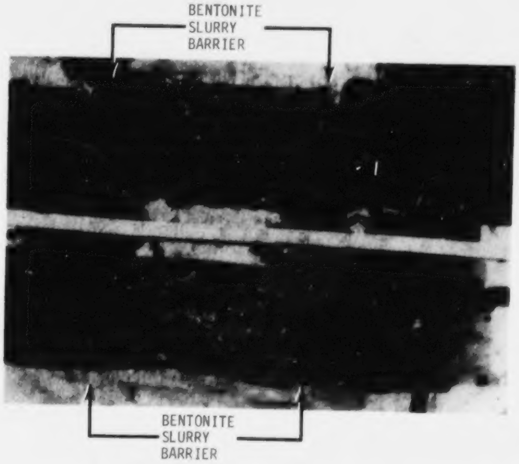

BENTONITE SLURRY BARRIER
BENTONITE SLURRY BARRIER

Figure 13. Core Sample #8 Showing Slurry Barrier Placed in Native Sand at 23 ft Depth

TECHNICAL ASSESSMENT OF DEMONSTRATION

The BDM demonstration yields three distinct technical conclusions:

- Based upon recovery of core samples from soil depths where bentonite clay slurry had been injected, the presence of bottom barrier material where expected was inferred.
- The perimeter barrier construction technique incorporated as part of the BDM process at Whitehouse was

unsatisfactory; conventional perimeter construction methods should be used in this and similar geologic materials.

- Data were collected which confirmed the applicability of construction materials, equipment, and field procedures used for bottom barrier emplacement at a specific site.

Based on this experience, it is estimated that the BDM could be applied to a variety of geological conditions, provided that careful attention is given to the specific properties of the earth in which the bottom seal will be placed. Soil pore sizes must be small enough to preclude excessive leakoff of slurry. Close proximity to solution channels or fractures should be avoided. Also discontinuities such as boulders and bedrock intrusions should be avoided. Finally, careful consideration must be given to exploit existing anisotropy and in situ stress conditions in order to successfully create the bottom separation and seal.

Foster-Miller concludes that the BDM is feasible and that the Whitehouse test, and the associated data acquired, showed sufficient demonstration of the key elements of the process to warrant further development and implementation. We also conclude that the process can be carried out in other areas where appropriate geology and soil properties exist, and where evaluation of these and other site-specific conditions shows a high probability for success. Finally, we conclude that the BDM is a process whose success depends on a number of site-specific variables, such as soil gradation, stratification, presence and extent of stratigraphic discontinuities, presence and nature of geologic fractures or solution channels, proximity and nature of utilities and foundations, and site access. Correct engineering decisions made with consideration of these and other variables are essential.

Based upon the experience obtained at Whitehouse, Florida, we recommend that application of the BDM should be based upon a thorough site evaluation and preliminary design phase. This should be followed by a small pilot program on-site to verify the success of notching and vertical separation at the base of an injection hole. This fracturing would subsequently be expanded underneath the entire planned block. A site performance verification program which includes monitoring of the barrier effectiveness should be implemented during and following block displacement.

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1. "User Guide for Evaluating Remedial Action Technologies," U.S. Environmental Protection Agency; to be published.

2. Cleary, J.M., "A Method for Displacing Large Blocks of Earth," U.S. Patent No. 4,230,368, February 1979.

3. Foster-Miller, Inc., Block Displacement Method Field Demonstration and Specifications, Final Report, to be issued to the Solid and Hazardous Waste Research Division, MERL, Office of Research and Development, USEPA, Cincinnati, OH under JRB Contract 60-03-3113, Task 37-1.

4. Brunsing, T.P., and W.E. Grube, Jr., "A Block Displacement Technique to Isolate Uncontrolled Hazardous Waste Sites," presented before the National Conference on Management of Uncontrolled Hazardous Waste Site, Hazardous Materials Control Research Institute, Silver Spring, MD, 1982.

THE IMPACT OF TOP-SEALING AT THE WINDHAM CONNECTICUT LANDFILL

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ABSTRACT

The landfill in Windham, Connecticut was operated from the late 1940s until 1979. In 1976, it was shown to be generating leachate and to be contaminating ground water moving downgradient toward a public water supply reservoir. In 1978-1980, SMC Martin designed and implemented a closure plan for the landfill which included regrading, installation of an impermeable PVC top seal, and revegetation. Total closure costs amounted to $0.44 per square foot. Investigations of the structural integrity of the top seal were conducted in 1980. These investigations indicated a minimal number of small punctures occurred in the top seal membrane. Spring recharge was effectively intercepted by the membrane and diverted from the landfill. The area of the plume of contamination was found to have been reduced. It is concluded that the top seal installed over the landfill has effectively reduced generation of leachate. Water erosion of the surface soils resulted after heavy spring rains but was corrected before damage to the membrane occurred.

INTRODUCTION

SMC Martin, under contract to U.S. EPA (#68-03-2519) developed and implemented a program of remedial action at an inoperative waste disposal site and monitored the effects of such action on water quality. Based on a number of physical and institutional criteria (landfill size, accessibility, representativeness; existence of a serious pollution problem; availability of basic engineering and geologic data for the site; availability of co-funding; freedom from litigation), an extensive evaluation of more than 400 landfills was conducted and the Windham, Connecticut landfill selected as the most suitable for implementation of the project.

After a preliminary investigation of site conditions, several possible remedial actions were evaluated. The principal purpose of remediation was to reduce the generation of leachate at the landfill and minimize its impact on surface and ground-water quality. The methods considered included surface diversion ditches, a slurry trench cutoff wall, a subsurface drainage system or a network of wells designed to lower the water table, and an impermeable top seal. This last was found to be the most practical and cost effective for the site and was applied to the landfill in conjunction with regrading and revegetation. This paper reviews physical conditions at the landfill and the specifics of landfill closure and discusses water quality improvements that resulted from remediation.

PHYSICAL SETTING AND EXISTING CONDITIONS

Windham Landfill is located in east-central Connecticut, just north of the City of Willimantic (Figure 1), on a site framed by the Windham Airport to the south and southeast, Mansfield Hollow reservoir to the east and northeast, and Willimantic reservoir to the west (Figure 2). Both reservoirs are situated on the Natchaug River. The stage in Mansfield Hollow reservoir, operated by the U.S. Army Corps of Engineers for flood control, is generally 6 meters (20 feet) higher than in Willimantic reservoir, a public water supply.

Subsurface materials in the area consist of granite gneiss bedrock overlain by more than 100 feet of fine-grained, poorly-sorted stratified glacial drift. Surface topography is highly irregular, marked by the hummocks and kettles characteristic of glacial terrain. Many surface depressions between the landfill and Willimantic reservoir are filled with small ponds.

Ground water occurs under water-table conditions in the unconsolidated drift at a depth of 7.5 to 9 meters (25 to 30 feet) near the landfill. Two types of material were distinguished during drilling: a buff-colored, poorly-sorted medium to fine-grained sand and gravel near the surface, and a gray, fine-grained sand and silt occurring below a depth of about 7.5 meters (25 feet). These materials are highly heterogeneous and only moderately permeable. An aquifer test performed in July 1978 yielded values of transmissivity between 1 and 10 m^2/day (10 and 100 ft^2/day). Water is recharged to the area primarily by infiltration of precipitation and occasionally by seepage from Mansfield Hollow reservoir. It flows northwest and west and discharges into Willimantic reservoir.

The Windham Landfill began as an open-burning dump adjacent to a pond in the 1940s. The pond was eventually filled in and the wastes covered with 5 to 6 m (15-20 ft) of demolition materials. Landfill operation continued in excavated trenches west of the old fill. In 1978, the site consisted of two mounded fill areas separated by a drainage pipe for the airport, occupying a total area of 10 hectares (25 acres).

SITE INVESTIGATIONS PRIOR TO CLOSURE

An initial investigation was conducted at the Windham Landfill site in 1975 and 1976 under the direction of the Connecticut Department of Environmental Protection (Griswold and Fuss, Inc., 1976). Further background data were gathered by SMC Martin during a drilling and sampling program from 1977 to 1979 (Emrich and Beck, 1979).

Results from this phase of the study indicated that the thickness of fill underlying the older eastern section of the site reached 15 m (50 ft) with 6 m (20 ft) of refuse occurring below the water table. The newer western section had a total thickness of 10 m (33 ft) occurring entirely above the water table. A plume of contamination, defined by means of an electrical resistivity survey and ground-water sampling, was found to emanate from the landfill and extend west-northwest and downgradient to the Willimantic reservoir. Chemical analyses of ground water from two wells sampled in May 1979, one upgradient and one downgradient from the landfill, are reproduced in Table 1.

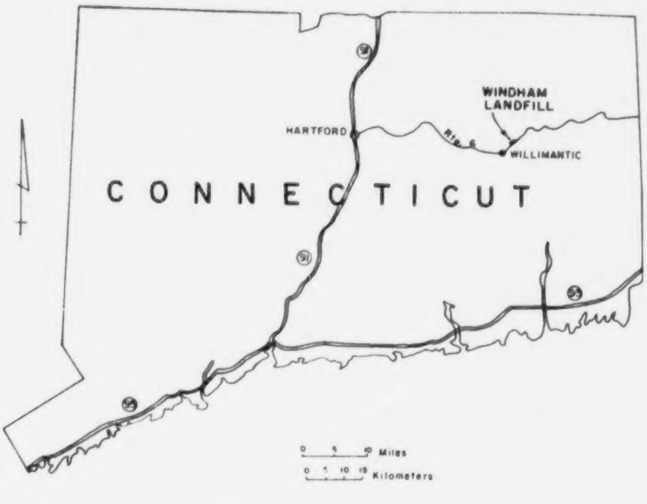
WINDHAM LANDFILL
HARTFORD
WILLIMANTIC
Rte 6
CONNECTICUT
Miles
Kilometers

Figure 1. Location Map for the Windham Landfill

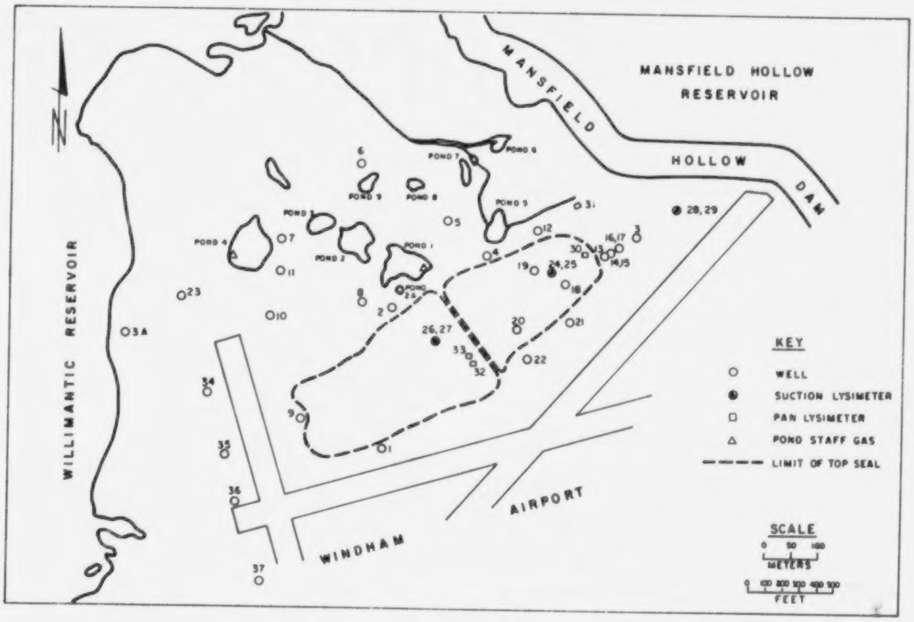
MANSFIELD HOLLOW RESERVOIR
MANSFIELD HOLLOW DAM
WILLIMANTIC RESERVOIR
POND 1
POND 2
POND 3
POND 4
POND 5
POND 6
POND 7
POND 8
POND 9
POND 2A
WINDHAM AIRPORT
KEY
WELL
SUCTION LYSIMETER
PAN LYSIMETER
POND STAFF GAS
LIMIT OF TOP SEAL
SCALE
METERS
FEET

Figure 2. Site Map for the Windham Landfill

TABLE 1

CHEMICAL PARAMETERS OF GROUND WATER UPGRADIENT AND DOWNGRADIENT FROM THE LANDFILL BEFORE CLOSURE (MAY 16, 1979)

Parameters	Well #1 (Upgradient)	Well #2 (Downgradient)
Temperature (°C)	11	12
pH	7.2	6.4
Specific Conductance (umhos)	200	1000
Total Solids (mg/l)	368	738
Alkalinity (mg/l)	25	376
Chloride (mg/l)	15	90
Total Organic Carbon (mg/l)	6.2	28.0
Iron (mg/l)	2.83	176.00
Manganese (mg/l)	0.23	2.05
Sodium (mg/l)	3.7	45.0
Copper (mg/l)	0.03	0.03
Lead (mg/l)	0.03	0.03

LANDFILL CLOSURE: METHOD AND COSTS

The closure plan developed by SMC Martin for Windham Landfill was designed to effectively seal out vertical seepage into the landfill and meet ground-water requirements of the Connecticut Department of Environmental Protection. The plan included regrading of the landfill, excavation of surface diversion ditches around the landfill, installation of an impermeable cover over the entire surface of the landfill and under the diversion ditches, and revegetation. The landfill cover actually consists of four layers (Figure 3): an intermediate sand and gravel cover immediately above the regraded waste materials, a 10-cm (4-in) sand bed designed to protect the overlying membrane, a 20-mil flexible PVC membrane, and a 45-cm (18-in) final cover of sand and gravel. Sewage sludge and composted leaves were subsequently harrowed into the final cover and seeded with grass. The closure was begun in July 1979 and completed in March 1980.

The costs involved in the closure of the Windham Landfill have been summarized in Table 2. Total costs amounted to approximately 44¢ per square foot, with the cost of the liner representing 80 percent of the total. It should be noted that sand and gravel used in the intermediate and final covers were obtained free of charge from nearby borrow areas.

TOP SEAL INTEGRITY

In April 1980 an investigation of selected areas was conducted at the site to determine the membrane's integrity. Seven excavations (test pits) were made by hand through the cover material to the membrane in both the old and the new sections of the landfill. It was determined that the membrane maintained its integrity during the placement of the cover material. Although there were numerous indentations up to 4 cm (1-1/2 in) deep in the membrane, there was no evidence of puncture. These indentations were caused by the final cover material which consisted of both sand and gravel.

The thickness of the cover material on the eastern (old)

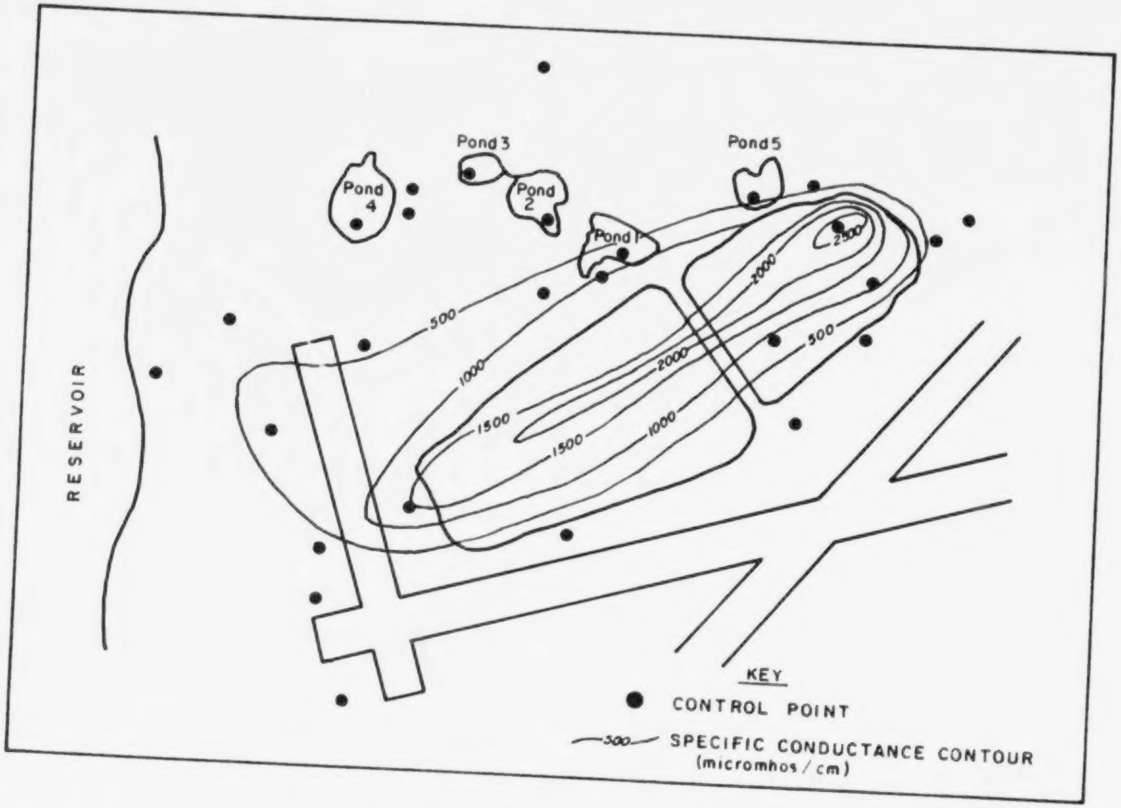
RESERVOIR
Pond 4
Pond 3
Pond 2
Pond 1
Pond 5
500
1000
1500
2000
2500
KEY
CONTROL POINT
500 SPECIFIC CONDUCTANCE CONTOUR (micromhos / cm)

Figure 3. Distribution of Specific Conductance, May 16, 1979

TABLE 2

CLOSURE COSTS FOR THE
WINDHAM, CONNECTICUT LANDFILL

Item	Costs, in Dollars Total	Per Acre	Per Square Foot
1. Grading and Compaction	105,000	4,200	0.096
2. Sand Blanket	48,000	1,920	0.044
3. Liner	219,000	8,760	0.201
4. Final Sand and Gravel Cover	80,000	3,200	0.073
5. Seeding	22,000	880	0.020
6. TOTAL	474,000	18,960	0.435

landfill varied from 10 to 46 cm (8 to 18 in). On the western section of the landfill (new) final cover varied from 38 to 46 cm (15 to 18 in). During the placement of the cover material over the seal, truck traffic patterns had to be established to assure a logical and systematic completion of the project. Several areas of high truck traffic were selected for investigation. The results of this investigation showed no visible punctures in the seal.

In May 1980, the integrity of the membrane was again inspected by staff members from EPA and the U.S. Corps of Engineers, Waterways Experiment Station, Vicksburg, MS. Three additional test pits were dug on the two sections of the landfill. Sections of the membrane seal were removed for testing and the membrane was patched using similar material and solvent welds. Several breaks in the membrane were observed in one section when it was held up to the light. The maximum break was one-quarter of an inch in length. All breaks were produced by punctures from the top down.

It was concluded from these studies that even in areas of heaviest truck traffic there were only a few breaks in the membrane and these breaks did not significantly reduce the effectiveness of the membrane to stop the movement of water in the cover material. Therefore, it was concluded that the majority of the infiltration was moving down to the membrane and then moved horizontally across the surface of the membrane discharging at the edges of the refuse into a land drainage swale.

During the first year severe water erosion occurred on the steep back slopes and in the swale between the two landfills after heavy spring rainfalls. This condition was investigated and corrective actions taken (Lutton, et al., 1981). The assessment concluded that water was washing away the fine grained sand and that there was no apparent damage to the membrane liner.

MONITORING

The monitoring network installed in and around the landfill during the course of this project is depicted in Figure 2. It includes the following:

1. Twenty-eight monitor wells in and around the landfill to obtain groundwater samples and groundwater level measurements.
2. Three pairs of suction lysimeters installed in each of the two landfill sections and upgradient from the landfill to obtain samples of soil moisture and leachate from two depths in the unsaturated zone.
3. Four pan lysimeters, including three in the landfill and one in sand and gravel, to check on the rate of vertical infiltration.
4. Two surface ponds downgradient from the landfill to obtain samples for analysis and additional water-level measurements.

From February to July 1979, water levels were measured weekly and samples taken monthly in existing wells and lysimeters. From July 1980 to May 1982, water level measurements have been made and samples taken on a bimonthly basis. Temperature, pH and specific conductance were measured on-site in all samples. Laboratory analyses were made for nine other parameters: total solids, alkalinity, chloride, total organic carbon, iron, manganese, sodium, copper, and lead.

The degree of water quality improvement which has occurred was illustrated in the comparison of Figures 3, 4 and 5 as discussed by Beck, et al (1981). In these figures, values of specific conductance measured on three different dates have been contoured to depict the plume of contamination spreading west-northwest from the landfill. Background values of specific conductance, measured at a well south of the airport, range from 100 to 400 umhos/cm. Ground water exhibiting a specific conductance higher than 500 umhos/cm has been assumed to be contaminated by leachate. Between May 1979 and May 1981, there was a 30 percent reduction in the area of contaminated ground water, but the degree of contamination beneath the eastern section of the landfill, where waste materials where partially saturated with ground water, was still very high. By November 1981, however, the plume had receded even further and conductivities measured beneath the eastern half of the landfill had decreased by 30 percent from their May 1979 values. The leachate plume, as depicted by the 500-umhos/cm contour line, had moved closer to the reservoir, which is the direction of groundwater flow.

Since the preparation of these figures the water quality has stabilized in the vicinity of the landfill. Recent results have shown that the area of contamination has not changed significantly during 1982.

CONCLUSION

By May 1982, water quality in the area surrounding Windham Landfill had been monitored for 40 months, including 26 months since top-sealing of the landfill had been completed. During that time, reductions in constituent levels were observed in wells downgradient from the landfill, and the plume of contamination emanating from the fill appeared to recede in area and is now stabilizing.

ACKNOWLEDGMENTS

This paper addresses one phase of a multiphase project being conducted by SMC Martin under U.S. EPA Contract No. 68-03-2519,

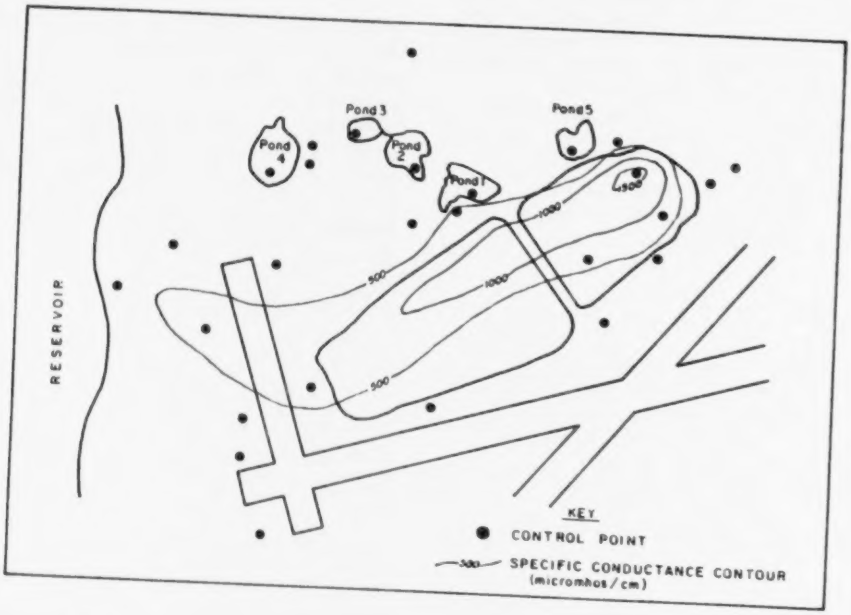
Pond 3
Pond 5
Pond 4
Pond 2
Pond 1
RESERVOIR
500
1000
1500
500
1000
500
KEY
CONTROL POINT
500 SPECIFIC CONDUCTANCE CONTOUR (micromhos/cm)

Figure 4. Distribution of Specific Conductance, November 12, 1981

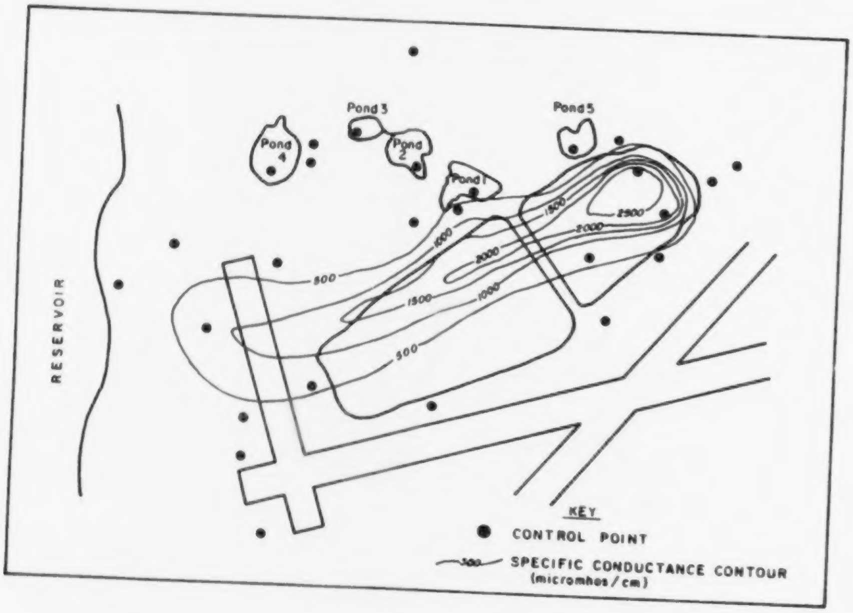
Pond 3
Pond 5
Pond 4
Pond 2
Pond 1
RESERVOIR
1500
2500
2000
1000
2000
500
1500
1000
500
KEY
CONTROL POINT
500 SPECIFIC CONDUCTANCE CONTOUR (micromhos/cm)

Figure 5. Distribution of Specific Conductance, May 19, 1981

Donald E. Sanning, Project Officer. Other phases involved the selection of an abandoned waste disposal site for study; the production of Guidance Manual for Minimizing Pollution from Waste Disposal Sites (EPA-600/2-27-142), a comprehensive discussion of remedial measures and estimates of their costs; the design and implementation of remedial neutralization procedures at the Windham, CT Landfill, and the implementation of a monitoring program to determine the effectiveness of the procedures.

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EVALUATION OF REMEDIAL ACTION ALTERNATIVES--DEMONSTRATION/APPLICATION OF GROUNDWATER MODELING TECHNOLOGY

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INTRODUCTION

The LaBounty landfill was an active chemical waste disposal site from 1953 to 1977. During this period, it is estimated that over 181,000 cubic meters (6.3 million cubic feet) of chemical waste were disposed in this 4.86 hectare (12.0 acre) site located in the flood plain of the Cedar River in Charles City, Iowa. Compounds that are known to be dumped in significant quantities include arsenic, orthonitroaniline (ONA), 1,1,2-Trichloroethane (TCE), phenols, and nitrobenzene. Disposal ceased in December 1977 following the discovery that wastes from the site were entering the river. Since that discovery, the LaBounty landfill has been under intensive investigation.

One aspect of these investigations was the ground-water modeling effort described in this paper. The overall objective of this modeling effort was to demonstrate the use of modeling technology for evaluating the effectiveness of existing and proposed remedial action alternatives at the site. The primary emphasis of the project was on technology demonstration which included:

- modeling of the ground-water system and prediction of the movement of contaminants,
- development of criteria to determine which water sources impacted by the site will require remedial action and the level of action necessary to insure risks are at acceptable levels, and
- the evaluation of the costs and effectiveness of various remedial action alternatives.

DESCRIPTION OF THE STUDY AREA

The LaBounty landfill site is located on the floodplain of the Cedar River just South of Charles City, Iowa. Charles City is in Floyd County which is situated in northeastern Iowa. The site sits on alluvial sand and gravel overlying a bedrock formation (Cedar Valley formation). Glacial tills have been found along the west side of the site above the Cedar Valley formation. The Cedar Valley formation can be divided into upper and lower units separated by a shale layer which acts as a confining layer at the site (1,2).

The hydrology of the LaBounty site is somewhat complex in that regional potential contours for the upper Cedar Valley aquifer and the shallow alluvial ground-water system indicate that the river acts as the major discharge area. In order to accurately represent the site with a model it is necessary to simulate this vertical movement.

MODEL DEVELOPMENT

Two computer codes were used to model the LaBounty landfill study area: FE3DGW (3) and CFEST (4). The FE3DGW code is a three-dimensional, finite-element, ground-water flow code that can be used to predict ground water potentials and water flow paths and travel times. The CFEST (Coupled Flow, Energy, and Solute Transport) code is an extension of FE3DGW that predicts the movement of contaminants with the convective dispersion equation for contaminant transport.

In order to better characterize the ground-water system at the LaBounty site, a two-stage modeling approach was used. The first stage consisted of developing a coarse grid regional hydrologic flow model, and the second stage consisted of developing a flow and contaminant transport model for the immediate vicinity of the LaBounty site. The purpose of the regional model was to establish hydrologic boundary conditions for the local model.

Regional Flow Model Implementation

The coarse grid regional model covers an area of 6.3 km by 4.8 km (approximately 3 miles by 4 miles). The regional boundaries were chosen such that the equal potential contours could be assumed nearly vertical with depth, or at a distance far enough away that errors in the assigned potentials did not influence local model boundary conditions.

The finite element grid pattern used to represent the large region is shown in Figure 1. The local model finite element grid boundaries superimpose onto the regional element pattern at the site.

Five different material types (layers) were simulated in the regional model. The lower layers, upper and lower bedrock and shale, are present over the entire model region. The alluvial layer exists along the Cedar River from a point north of Charles City southeast to the model boundary (Figure 1). A combined fill and till layer was simulated in the area of the LaBounty Site. The structural top and ground-water potential for the layers were taken from data contained in Munter (2). Hydraulic conductivities (K) of the layers were initially set at average values obtained from several sources (1,2,5,6,7) and the vertical to horizontal permeability ratio (K_z/K_{xy}) was set at 0.1.

Initially it was assumed that 10% of the total precipitation of 900 mm (35 in.) (7) recharged the ground-water system. This was the only source of recharge considered.

Local Flow Model Implementation

The local model covers the area just in the immediate vicinity of the LaBounty site (Figure 1) and is 685 m (2,250 ft) on a side. The Cedar River forms the boundary to the north, east, and south while the western boundary was arbitrarily set to the west of the fill material.

The finite element grid pattern used to represent the small region is also shown in Figure 2. The same materials simulated in the large region were simulated in the small region except that the fill and till were modeled separately.

The structural top and bottom and potentiometric surfaces for the shale and bedrock layers were defined the same as in the regional model. More detailed structure and potential surfaces were prepared for the local model alluvium, fill and till layers with data obtained from Munter (2).

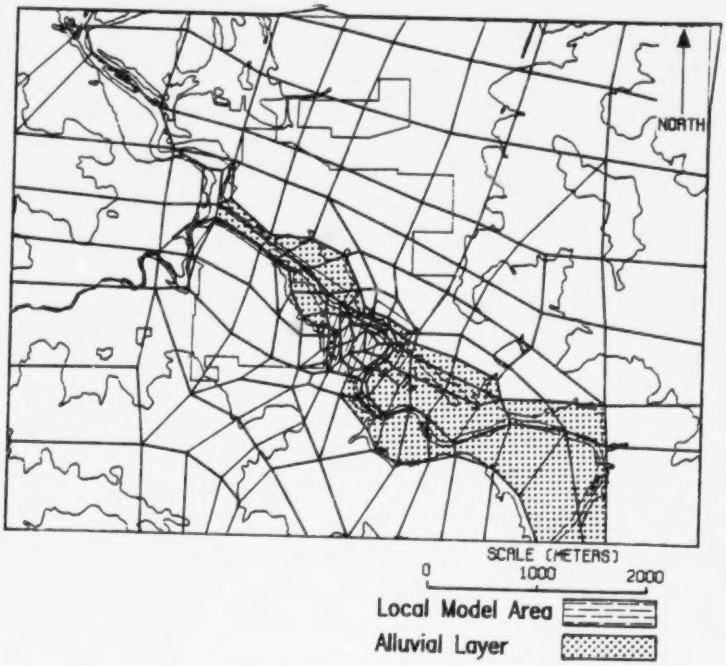
NORTH
SCALE (METERS)
0
1000
2000
Local Model Area
Alluvial Layer

FIGURE 1. Legion Region Model Finite Element Grid

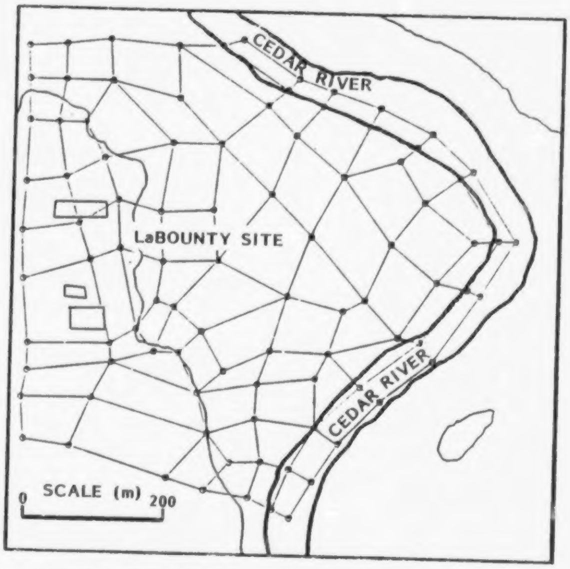
CEDAR RIVER
LaBOUNTY SITE
CEDAR RIVER
0 SCALE (m) 200

FIGURE 2. Local Ground-Water Flow Model Finite Element Grid

Stage data for the Cedar River were extrapolated to obtain held river elevations along the model boundary. The same permeabilities and recharge rate used in the regional model were initially used in the local model.

Local Contaminant Transport Model Implementation

The CFEST code was used to simulate the movement of arsenic from the landfill to the Cedar River in the local model region and to test the effectiveness of the proposed remedial action alternatives in controlling the arsenic plume. Since the ground-water flow portion of CFEST is identical to FE3DGW, the final calibrated FE3DGW data set was used directly in CFEST to predict ground-water flow. The additional inputs required by the CFEST code to simulate contaminant transport were longitudinal (D_L) and transverse (D_T) dispersivity and initial contaminant concentration levels. Initially D_L and D_T were set at 30.0 m and 0.5 m, respectively. Arsenic was chosen for use in the calibration and remedial action simulations because it has been extensively monitored and its source is fairly uniformly distributed over the area of the fill material.

It is thought that arsenic enters the ground-water flow system from two sources:
1) precipitation infiltrating through the fill material, and
2) leaching due to fill material being below the water table. The location of the saturated portion of the fill was determined from the literature (2,5) to be in two places as shown on Figure 3. For modeling purposes these two sources were simulated by holding the down-gradient surface nodes of the saturated fill layer at an arsenic concentration of 500 mg/l. Water infiltrating through the cap was also assigned an arsenic concentration of 500 mg/l.

MODEL CALIBRATION

The flow model calibration process consisted of matching observed potentials with model predicted potentials for both the regional and local models. Calibration was accomplished by first calibrating the regional model and then testing the local model with a consistent set of input data. This alternating process was carried out until a satisfactory agreement between measured and model-predicted heads was achieved in both models.

The final input parameters obtained for the local model were then used in the contaminant transport model. These parameters were not changed in the contaminant transport calibration process. Parameters related to contaminant transport were adjusted to obtain a reasonable match between field-measured and model-predicted contaminant concentrations.

Flow Model Calibration

The parameters adjusted in the flow model calibration process were the hydraulic conductivities (K), the ratio of vertical to horizontal hydraulic conductivities (K_z/K_x), the specific storage, and the rate of recharge. After several calibration runs, a good match was achieved between measured and model-predicted potentials for both the regional and local models. The final calibrated hydraulic conductivities and storages used in the flow models are listed in Table 1. More detailed recharge calculations estimated that about 14% of the precipitation (126 mm/yr) reached the ground water.

Contaminant Transport Model Calibration

One of the first changes made was to change the node and element grid to allow for a more accurate description of the location of the arsenic source and better represent

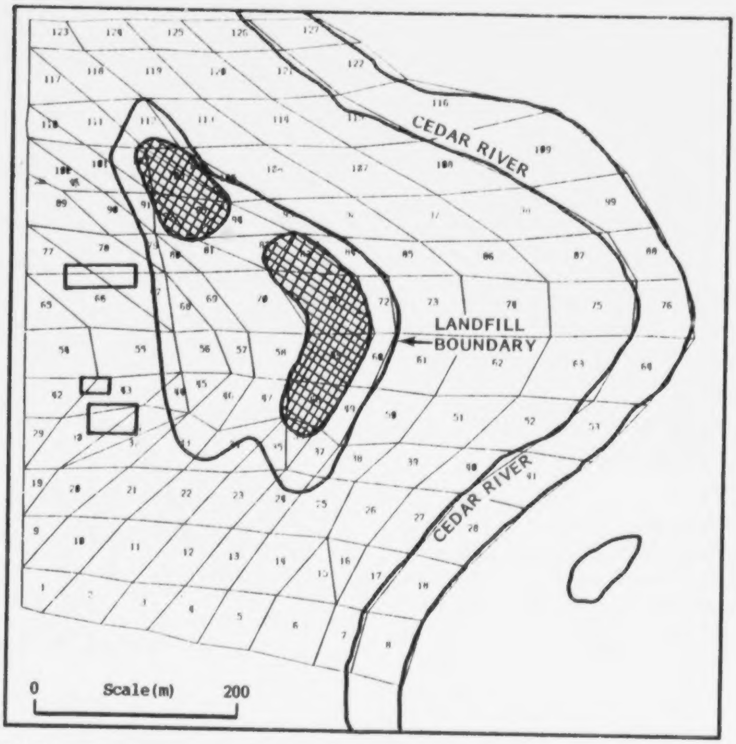

FIGURE 3. Contaminant Transport Model Finite Element Grid. Crosshatched area indicates area determined to be below the water table.

TABLE 1. INPUT VALUES USED IN THE FINAL CALIBRATED FLOW MODELS

Layer (Small)	Material	K* (m/day)	Specific Storage (1/m)	K_z/K_x Ratio
1*	Fill	0.5	0.0025	0.1
2	Aluvium	10 and 2	0.01	0.1
3	Till	5×10^{-4}	0.0025	0.1
4	Upper Cedar Valley	2.0 and 4.0	10^{-4}	0.1
5	Shale	2.0 and 5×10^{-3}	10^{-4}	0.1
6	Lower Cedar Valley	2.0	10^{-4}	0.1

* Where two values of K are given, the first number listed covered the largest percentage of the total area covered by that material.

† The fill and till layers were combined into one layer in the regional model with a K of 10^{-3} m/day.

the spread of the resulting arsenic plume. The finite element grid used in all subsequent calibration runs and in the remedial action cases is shown in Figure 3.

Different values of longitudinal and transverse dispersivity were tested in order to match model-predicted with measured arsenic concentration levels. The results of these test runs indicated that longitudinal and transverse dispersivities of 5.0 m and 0.5 m, respectively, gave the best results. The initial concentration level for arsenic of 500 mg/l was not changed in the calibration process.

The last step in the calibration process was to determine the location of the arsenic source (5). As stated above, it was suspected that arsenic enters the flow system from either infiltration alone, or a combination of infiltration and ground-water leaching where fill material is thought to be below the water table. Both cases were tested by comparing model-predicted arsenic concentrations and river loading quantities against field-measured levels.

After running both cases for 6000 days it became apparent that the case of infiltration alone would never achieve the arsenic levels that have been measured at the site. The results indicate that part of the fill material must indeed be below the water table and that the majority of the contaminant transport is originating in the saturated ground-water system and not in the unsaturated flow system as a result of infiltration.

Based on these findings the final calibrated model, hereafter referred to as the base case, included both sources of arsenic, infiltration and groundwater leaching. A contour map of the base case arsenic concentrations after 6000 days (near equilibrium) is shown in Figure 4. This final calibrated contaminant transport model base case became the initial condition from which all the remedial action cases were initiated.

The final calibrated transport model predicted arsenic mass outflow rate to the river was 25.2 kg/day (55.4 lb/day). The average mass outflow rate as measured by the monitoring system at the site is 22.7 kg/day (50.0 lb/day).

ASSESSMENT OF REMEDIAL ACTION ALTERNATIVES

Seven remedial action alternatives were identified for potential application to the LaBounty landfill site and were modeled with the CFEST model; clay cap, upgradient cutoff wall, downgradient cutoff wall, limited excavation, limited bottom lining, stabilization, and pump and treat. The clay cap alternative has already been implemented at the site.

Contaminant transport model parameters were adjusted to simulate arsenic migration to the river for each alternative. The alternatives were assessed by first quantifying their effectiveness on reducing contaminant concentrations and Cedar River loading rates. These results were compared with the results for the clay cap alternative to obtain a measure of effectiveness.

The next step was to estimate the capital and annual operating and maintenance costs associated with each alternative. Given the effectiveness and cost, the final step was to make a cost-effectiveness comparison of the alternatives.

The base case, as discussed earlier, was run for 6000 days (16.4 years). Each remedial action case was run for an additional 4500 days (12.3 years) beginning at the end of the 6000-day period.

Clay Cap

The clay cap alternative was modeled by reducing the infiltration rate by a factor of 100 in the area of the cap. The magnitude of the decrease was estimated using a

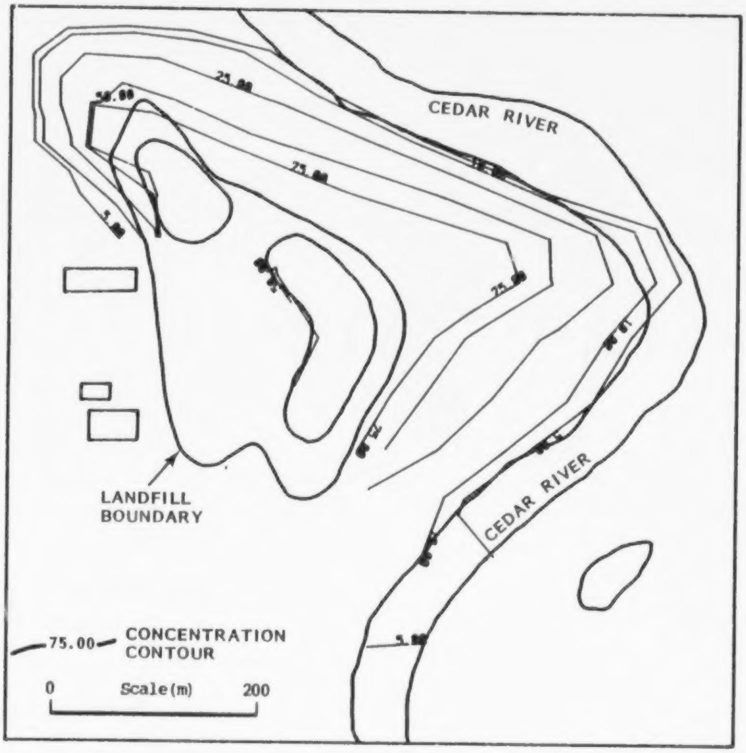

FIGURE 4. Arsenic Concentrations (mg/l) at the Top of the Alluvium for the Base Case of Combined Infiltration and Disposal Below the Water Table

simple compartmental model and a permeability for clay of 3 x 10^{-5} m/day. The rate of arsenic injection from infiltration was also reduced by a factor of 100 to 0.08 kg/day (0.04 lb/day).

The results of this run indicated a continued but slight rise in predicted arsenic loading of the Cedar River 27.5 kg/day (60.4 lb/day) after 4500 days, again illustrating that the portion of the waste disposed below the water table is the major source of the contamination problem at LaBounty. The clay cap was assumed to be in place for simulation of the remaining six remedial action alternatives.

Upgradient Cutoff Wall

The objective of the upgradient cutoff wall is to reroute incoming ground water such that it bypasses waste contaminated soil. This can only work if the wall extends downward to an impermeable layer or incorporates some means of transport to carry off water mounded behind the wall. Since the dolomite base rock at Charles City is transmissive, the latter would be required. For the purposes of this evaluation, it was assumed that a subsurface drain is constructed upgradient from the cutoff wall to carry uncontaminated water away from the site.

The effectiveness of the upgradient cutoff wall was simulated by introducing a line of elements with low permeability upgradient of the landfill (Figure 5). The upstream set of surface nodes along the low permeability cutoff wall were treated as held potential boundary nodes to simulate the

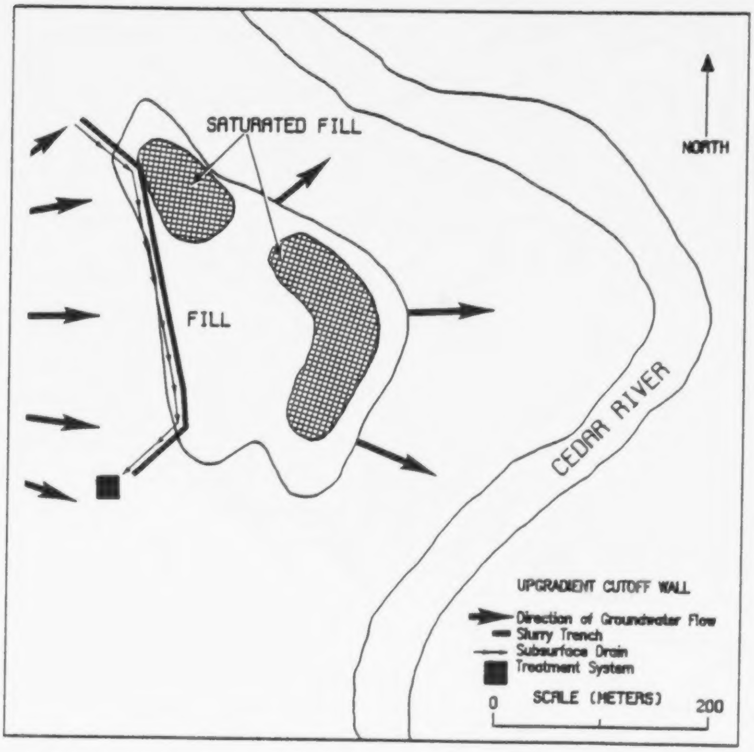
SATURATED FILL
FILL
NORTH
CEDAR RIVER
UPGRADIENT CUTOFF WALL
Direction of Groundwater Flow
Slurry Trench
Subsurface Drain
Treatment System
SCALE (METERS)
0
200

FIGURE 5. Upgradient Cutoff Wall Remedial Action Alternative

upgradient drain. The flux to these held nodes was calculated to determine the required capacity of the subsurface drain associated with this alternative.

The results of this analysis indicate that new equilibrium is reached in about 5 years with Cedar River loading rate reduced to 14.9 kg/day (32 lbs/day) after 4500 days.

Downgradient Cutoff Wall

The downgradient cutoff wall is intended to intercept contaminated ground water and then route it via drains for treatment. The effectiveness of the downgradient cutoff wall was simulated in the model with a line of impermeable elements downgradient from the site (Figure 6). The upstream set of surface nodes formed the simulated drain and were treated as a held potential outflow boundary. The flux to these nodes and arsenic concentration levels were predicted to determine the capacity of the subsurface drain and the treatment facility.

Results of this simulation indicate that new equilibrium river loading rates were achieved after approximately 3 years, 2 years faster than for the upgradient case. The new Cedar River loading rate predicted at the end of 4500 days was 7.66 kg/day (16.9 lb/day).

Limited Excavation

The intent of the limited excavation approach is to remove those portions of the waste below the water table and to backfill with clean fill.

Simulation of the limited excavation case with the model involved removing the source term

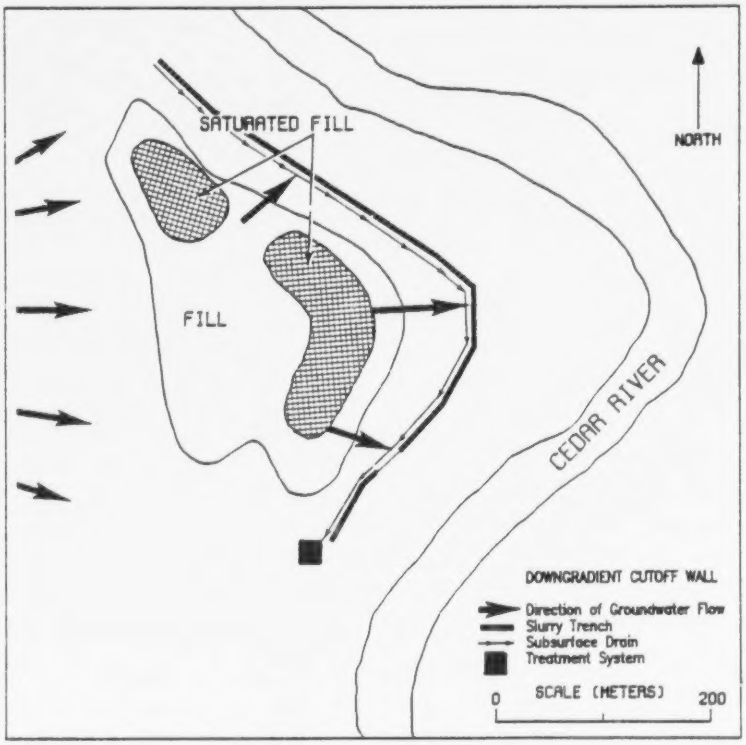

FIGURE 6. Downgradient Cutoff Wall Remedial Action Alternative

associated with wastes disposed below the water table and changing the permeability in the area where the fill material was removed to that of the alluvium. Figure 3 indicates the approximate size of the areas below the water table.

Results of this simulation indicate that this alternative provides a more delayed response in terms of river loading rates but that with time, much lower arrival rates could possibly be achieved. Model results indicated that after 4500 days predicted Cedar River loading has decreased to 8.0 kg/day (17.6 lb/day).

Limited Bottom Lining and Stabilization

These two approaches are very similar in that they are both isolation techniques, either through the use of a liner or fixation method. Only those portions of the waste below the water table would be lined or stabilized. Presumably, this would reduce water flux and hence minimize further contributions from these portions of the landfill to the overall contaminant plume. Stabilization presents a challenge to current technology since in situ fixation has not been perfected. Both of these alternatives were modeled in an identical manner.

The total source mass of waste remained the same as the base case but the leach rate was reduced. This was simulated in the model by changing the permeability in the saturated fill area to that of a clay (10^{-5} m/day).

The results for these alternatives are very similar to those of the limited excavation alternative. As with limited excavation, the reduction in Cedar River loading is more gradual but it has the possibility of eventually reaching much lower river loading rates. After 4500 days a Cedar River loading of 8.14 kg/day (17.9 lb/day) was predicted.

Pump and Treat

In this isolation method, removal is accomplished through use of a series of withdrawal wells (Figure 7). The water is subsequently treated to eliminate contaminants and either discharged back to the river or reinjected to assist in directing the contaminanted plume toward the wells.

Pumping rates were estimated at 1806 m^3/day (0.477 mgd). As with the downgradient cutoff wall, predicted concentrations for treatment during the first year is higher (71 ppm) but it soon levels off at about 34 ppm. Predicted Cedar River loading rates have pretty much equilibrated after 5 years and were predicted to reach 10.12 kg/day (22.3 lb/day) after 4500 days.

The capital cost and annual operating cost for all the alternatives are given in Table 2. It is important to note that for all cases these costs should be considered only as rough estimates, since they are based on preliminary conceptual designs for each alternative and they do not reflect local cost differences.

Discussion of Results

A comparison of arsenic mass outflow rates to the river for the base case and the seven remedial action alternatives as predicted by the model is shown in Figure 8. The contaminant transport model very clearly indicated that the major source of ground-water contamination arises from that portion of the arsenical sludge buried below the water table.

Model results indicate that only the clay cap and the upgradient cutoff wall would probably fail to bring river concentrations (under low flow conditions) below drinking water standards. The upgradient cutoff wall, however, could probably be significantly improved through optimization studies with the transport model. Optimization studies were not performed for any of the alternatives.

The remaining five alternatives all lowered river concentrations below drinking water standards for Cedar River low flow conditions; however, the selection of the best alternative is still very much subjective. The downgradient cutoff wall and pump and treat alternatives show a quick response in reducing contamination levels but they approach a higher Cedar River loading limit. On the other hand, the bottom lining, excavation, and stabilization alternatives do not respond as quickly but have the potential to achieve much lower Cedar River loading rates and aquifer contamination levels. Cost effectiveness of the various remediation alternatives is an important part of any decision making process. As indicated in Table 2, limited excavation (on site reburial) and bottom lining are the least cost alternatives (excluding the upgradient cutoff wall which failed to meet the level of contamination criteria). When comparing costs per unit reduction in predicted Cedar River arsenic concentrations (low river flow conditions) or the cost per unit reduction after 4500 days in arsenic contaminant mass in the saturated aquifer system, the limited excavation (on site reburial) is most cost-effective, followed by limited bottom lining and pump and treat. In both cases, stabilization is the least cost effective, followed by limited excavation (offsite reburial) and the downgradient cutoff wall.

CONCLUSIONS

A hydrologic flow and transport model of the Charles City LaBounty landfill was developed, calibrated and used to evaluate seven remedial action alternatives for the LaBounty site. This modeling study has

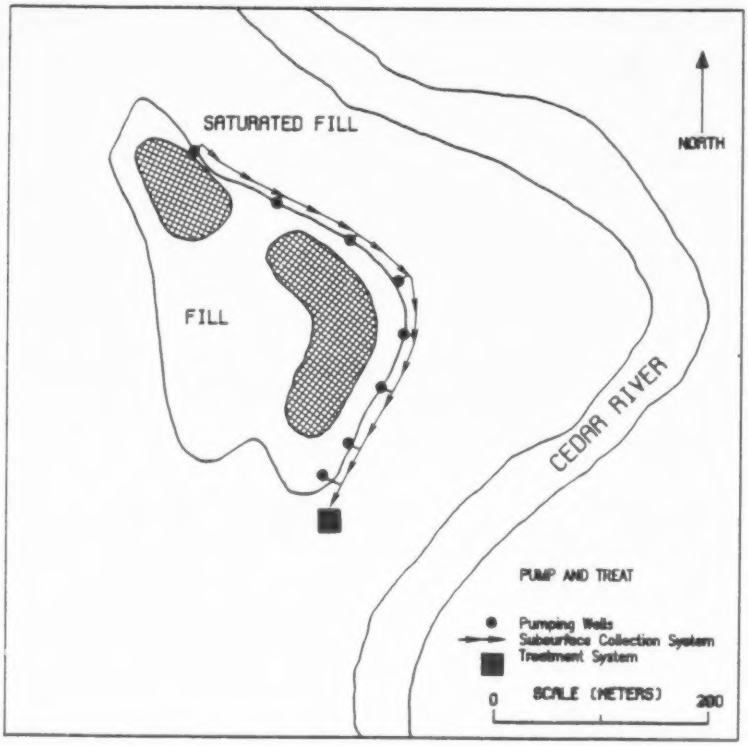
SATURATED FILL
FILL
NORTH
CEDAR RIVER
PUMP AND TREAT
Pumping Wells
Subsurface Collection System
Treatment System
0 SCALE (METERS) 200

FIGURE 7. Pump and Treat Remedial Action Alternative

TABLE 2. ESTIMATED COST FOR EACH OF THE SEVEN REMEDIATION ALTERNATIVES

Remediation Alternative	Capital Cost (dollars)	Annual Operating Cost (1982 dollars)
Upgradient cutoff wall* and treatment	835,000	99,000
Limited excavation** (on site reburial)	1,000,000	35,000
Limited bottom lining	1,348,000	67,000
Pump and treatment	1,431,000	168,000
Downgradient cutoff wall and treatment	2,569,000	114,000
Limited excavation (off site reburial)	16,000,000	35,000
Stabilization	16,787,000	35,000

* If optimized, costs for this alternative are likely to be higher since diversion of more water will most likely be required.

** Assumes that waste removed from below the water table would be reburied on site above the water table and capped with clay.

reaffirmed the importance of considering the regional hydrologic system when modeling the hydrology and transport for a more local system like LaBounty, and illustrates the value of groundwater modeling in developing an understanding of a complex flow and transport system. In the process of modeling the LaBounty site, it was demonstrated that boundary conditions for the local model cannot be arbitrarily set and still obtain reasonable estimates for travel time and river discharge rates. The contaminant transport model developed for the LaBounty site, while not a perfect indicator of observed contamination movement, is certainly an adequate indicator for the purpose of general understanding and for the evaluation of the effectiveness of various remedial action alternatives.

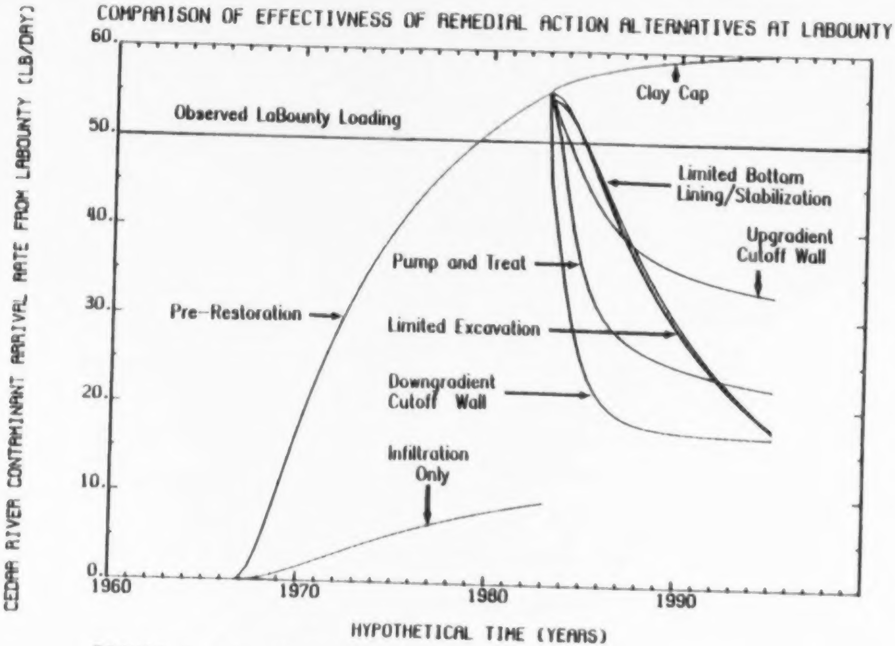

FIGURE 8. Predicted Effective of the Various Remediation Alternatives in Reducing the Arsenic Loading of the Cedar River.

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SLURRY TRENCH CONSTRUCTION OF POLLUTION MIGRATION CUT-OFF WALLS

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ABSTRACT

A technical handbook evaluating the use of slurry trench construction techniques for controlling pollution migration has recently been completed. This work, funded by the U.S. Environmental Protection Agency's Office of Research and Development, is intended to provide guidance to evaluators of proposed remedial actions that include subsurface barriers emplaced by slurry trenching. This paper updates the overview presented before the National Conference on Management of Uncontrolled Hazardous Waste Sites, in Washington, D.C., in November 1982. The technical aspects of slurry trench construction as it is applied to hazardous waste site groundwater control are discussed.

The materials used for trench excavation are described, along with their functions. Also described are the materials used to backfill the trench, forming the final cut-off wall. Emphasis is placed on the two most common backfill materials, soil-bentonite and cement-bentonite; their characteristics, and what is known of their compatibility with hazardous wastes. The way in which various cut-off wall configurations can be applied to a site are discussed and illustrated. Construction procedures for a typical soil-bentonite slurry wall are outlined, and examples of completed wall costs given.

INTRODUCTION

Over the last two decades, cut-off walls emplaced by slurry trenching have been installed at many solid and hazardous waste facilities. An overview of a draft Technical Handbook on construction of cut-off walls using slurry trench techniques was presented at the National Conference on Management of Uncontrolled Hazardous Waste sites in Washington, D.C., in November 1982. Following is an update of data interpretation and project accomplishements since the November report. This Handbook was prepared for EPA's Office of Research and Development to compile the scientific and technical parameters which need to be evaluated when considering this type of construction for isolation of hazardous chemicals in near-surface groundwater regimes. It contains sections which present the theory of slurry and backfill function, applicability of cut-off walls to curb groundwater migration, site investigations needed preliminary to construction, actual design and construction parameters, wall performance monitoring and maintenance, and presentation of major cost elements.

Slurry trenching is a method by which a continuous trench is excavated (by backhoe or clam-shell grab) under a slurry of bentonite and water. This slurry, or more correctly, colloidal suspension, supports the trench walls and allows excavation to great depths with no other means of support. Once a trench has been excavated under slurry to the required depth and length, it is back-filled to form a continuous, nearly impermeable barrier, or cut-off wall, to groundwater flow. In some cases, the slurry is a mixture of water, cement, and bentonite (CB backfill) which hardens in place to form the final barrier. In other instances, this trenching technique is used to place soil-bentonite (SB) cut-off walls, where the backfill is composed of the excavated soil with small amounts (1 to 4%) of bentonite added. In some instances, borrowed soil materials, such as additional fine grained materials, or gravel must be added to meet the requirements of lower permeability of higher strength. Another variation of this technique, seldom used for pollution migration control, is the use of pre-cast or cast-in-place concrete diaphragm walls, which are installed when both pollution migration cut-off and structural support are required. Because they are seldom used, diaphragm walls are not further discussed here. Table 1 lists some typical slurry walls installed for pollution control.

Slurry Materials and Function

The material used in the trenching slurry is a commercially available product called bentonite, sodium bentonite, or Wyoming bentonite. Bentonite is considered by many to be a clay but is in fact, a rock, composed mostly of the clay mineral montmorillonite, with smaller amounts of other clays and various metallic oxides. Montmorillonite crystals contain negative charges which attract and adsorb cations. In most bentonites, the montmorillonite is saturated with calcium ions: however, the products which are used for slurries and drilling muds are the Wyoming bentonites which bentonite is generally highly colloidal and plastic, and has the ability to swell many times its volume and to form thixotropic gels in water [1].

Many commercially available bentonite are modified by the addition of polymers, peptizers or other chemicals. This practice has been adopted in order to increase the amount of mud (slurry) yielded by lower grade bentonite deposits, and, in the case of polymer extended products, to increase piping resistance in liner applications.

The slurry used in trenching is composed of clean water mixed with from 5% to 7% premium grade bentonite by weight [2]. Make-up water should be low in dissolved salts and hardness, and neutral or slightly basic in pH. When introduced into the trench, the slurry should be fully hydrated with an "apparent viscosity" of from 15 to 20 centipoise and a density of approximately 65 pounds per cubic foot, (pcf)[3,4]. Where field practice uses the Marsh cone funnel to estimate slurry viscosity, a reading of at least 40 seconds is necessary to assure adequate filter cake formation and sufficient density to support the trench [2].

As stated earlier, the primary role of the slurry is to keep the trench open during excavation. A number of mechanisms have been suggested for trench support, including hydrostatic force exerted by the slurry, formation of a filter cake on the trench sides, and compaction of the earth on either side of the trench during excavation[5]. Of these three, the first two are the most important, and are closely related[5,6].

In order for the force exerted by the weight of the slurry to support the trench, the force must be exerted on the soil grains and not just on the soil pore fluids. The formation of a low permeability filter cake on the trench sides, caused by slurry and water loss from the trench into the ground, eventually seals

LOCATION	WALL COMPOSITION	SIZE* (ft.^{2} x 1000)	APPROXIMATE COST (\$/ft.^{2})	POLLUTANT CONTAINED	STATUS
Indiana	Soil-Bentonite	500	3	Inorganics Ash Disposal	On-going
Illinois	Soil-Bentonite	13.5	4	Methane Gas	Completed
Louisiana	Soil-Bentonite	30	2.5	Ethylene Dichloride	Completed
Pennsylvania	Cement-Bentonite	1	2	PCB Oils	Completed
New York	Cement-Bentonite	77.3	5.5	Jet Fuel	Completed
New Hampshire	Soil-Bentonite	204	5	Mixed Organics	On-going
Wisconsin	Soil-Bentonite	98.4	2.8	Solid Waste Landfill Leachate	Completed
New Jersey	Soil-Bentonite	10	6	Phenols	Completed
Saskatchewan	Soil-Bentonite	53.4	4	Uranium Mill Tailings	Completed
Florida	Soil-Bentonite	58	2.6	Methane Gas Landfill Leachate	Completed
Ohio	Soil-Bentonite & Cement-Bentonite	25	10	Acid Mine Drainage	Completed
Florida	Cement-Bentonite	10	4	Radioactive Kerosene	Completed

*These walls range from 2 to 4 feet in width and 15 to 100 feet in depth.

TABLE 1. Example Slurry Walls Installed For Pollution Control

off the soil pores, allowing the hydrostatic force of the slurry to be transferred more directly to the sides. Filter cake formation is a function of clay type, clay concentration in the slurry, and formation time and pressure. Permeabilities of filter cakes have been measured as low as 2.3×10^{-9} cm/sec [2,6]. Additional trench support can be expected by the plastering effect of the filter cake holding the soil grains together, and by gelation of the slurry in the soil pores into which it infiltrates [5]. The contribution of the filter cake to the final cut-off wall is examined later in this paper.

Backfill Materials and Function

There are three major types of slurry trench backfill: soil-bentonite (SB), cement-bentonite (CB), and concrete. The choice of backfill is dependent on specific site characteristics and the requirements of the completed cut-off wall. SB and CB cut-off walls are discussed below.

Soil-Bentonite Cut-Off Walls

Soil-bentonite (SB) cut-off walls are often backfilled using the soil materials excavated from the trench. These soils, or soils with more favorable properties borrowed from another source, are mixed with small amounts of slurry from the trench until they become a homogenous paste. The recommended consistency for the backfill is a mixture that will stand on a 5 to 10:1 slope (as measured by slump cone) with a water content of 25% to 35%. The minimum amount of bentonite in the backfill mixture will range from 0.5% ot 2% depending on the initial water conent of the excavated soil[2].

The permeability of the backfill is very much dependent on the gradation of the soil used, as well as on the bentonite content and intial water content of the backfill. The lowest permeabilities are obtained when the backfill is well graded and contains an appreciable amount (i.e., 10-20% or more) of fines (particles passing a 200 mesh sieve) an especially plastic fines[2]. Figure 1 shows the extent to which fines and plastic fines can affect backfill permeability. Figure 2 shows the contribution of added bentonite to the permeability of the backfill. In cases where the excavated soils are not well suited for backfill, borrowed soils may have to be added to meet the design criteria. For example, if low compressibility is called for in the design, and the trench materials lack coarser particles, additional sand or gravel may be needed. If low permeability is of greater concern than low compressibility, addition of borrowed coarser materials would be unnecessary. If fines are lacking in the trench soils, and low permeability backfill (1×10^{-7} cm/sec) is called for, borrowed material could be required. Bentonite can make up only a portion of the plastic fines in the backfill mixture due to its high compressibility. In brief, gradation of the backfill is a trade off between permeability and compressibility as illustrated in Figures 1 and 3.

The permeability of the final wall is a function of both the filter cake permeability and the backfill permeability. Because the backfill is less permeable than the surrounding soil it is possible that the downgradient filter cake is forced into the soil matrix under the hydraulic gradient across the wall. This gradient would act to force the upgradient filter cake into the backfill, but given proper backfill gradations (i.e., sufficient fines) it would remain intact [2]. Figure 4 illustrates the relative contribution of the backfill and one filter cake to the final wall permeability. This figure also shows that the contribution of the filter cake is greater for more permeable backfill and less for more impermeable backfill. It also illustrates that, even with very permeable backfill, the maximum permeability of a SB cut-off wall should be on the order of 1×10^{-6} cm/sec due to the contribution of one filter cake alone.

Cement-Bentonite Cut Off Walls

Cement-bentonite (CB) cut-off walls are of two major types: self-hardening slurries, which both support the trench and are allowed to harden in-place; and replacement slurries which are introduced into the trench following excavation using a bentonite-water slurry for trench support. Replacement slurries are used in very deep excavations or with time consuming rock key-ins where a self-hardening slurry would thicken or set before

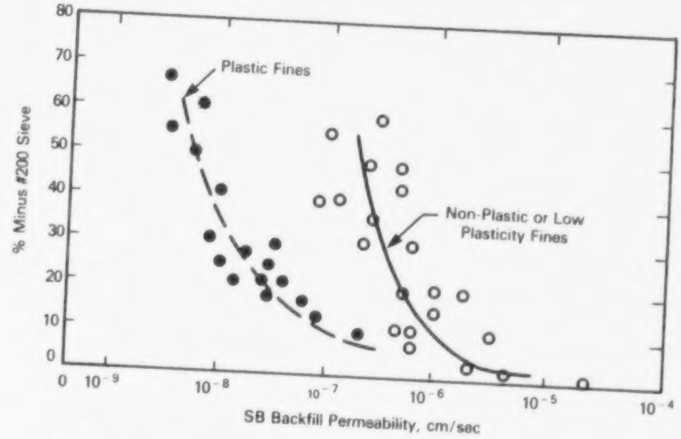


Figure 1. Permeability of Soil-Bentonite Backfill Related to Fines Content

(After D'Appolonia and Ryan 1979)

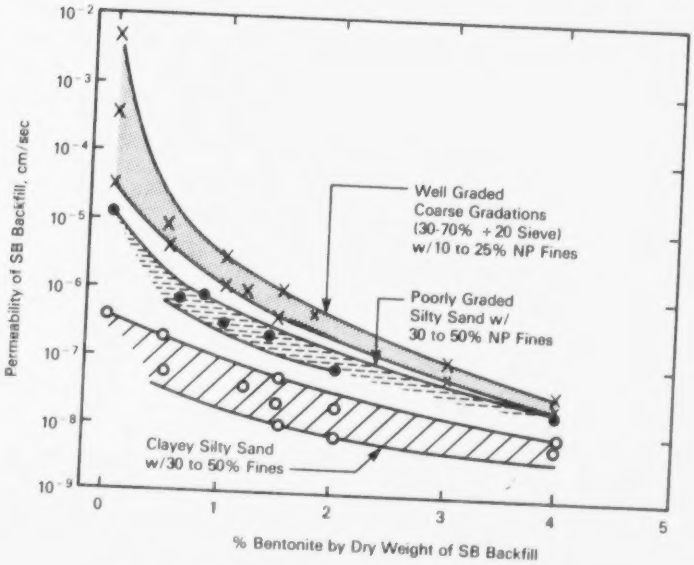


Figure 2. Relationship Between Permeability and Quantity of Bentonite Added to SB Backfill

(After D'Appolonia and Ryan 1979)

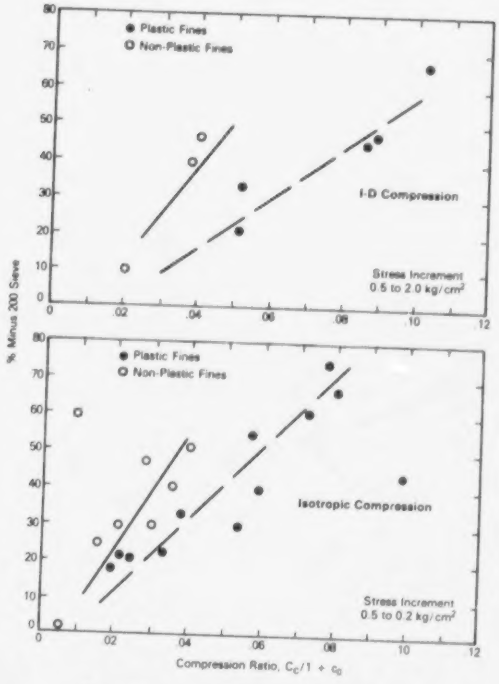
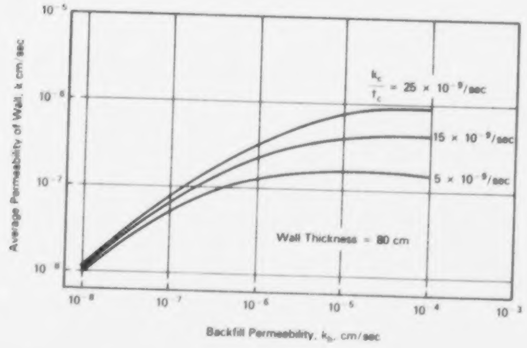


Figure 3. Compressibility of SB Backfill Related to Fines Content of Mix

(After D'Appolonia, 1980)



k = Wall Permeability
k_c = Cake Permeability
k_b = Backfill Permeability
t_b = Backfill Thickness
t_c = Cake Thickness

$$k = \frac{t_b}{\left(\frac{t_b}{k_b} + \frac{2t_c}{k_c}\right)}$$

Figure 4. Theoretical Relationship Between Wall Permeability and Permeability of the Filter Cake and Backfill

(After D'Appolonia and Ryan 1979)

excavation was complete. The self-hardening slurries are used in relatively shallow trenches (< 70') where their rapid set should not interfere with excavation.

Typically, a self-hardening CB slurry contains (by weight) from 4 to 7% bentonite, from 8 to 25% type I Portland cement, and from 68 to 88% water [7].

If too much bentonite and cement are used, the slurry may be too thick to work with. If too little cement is used, no set will be achieved; and if too little (or poor quality) bentonite is used, the cement will settle out of the slurry, causing excessive water bleeding. Figure 5 illustrates typical CB slurry compositions. The actual composition of the slurry is determined during the wall's design.

At the time the CB slurry is introduced into the trench, it typically has a density of about 68 PCF and a Marsh viscosity ranging from 30 to 50 seconds [7,8]. After excavation, but before set, it can have densities of around 78 pcf and will be too viscose to pass a Marsh funnel[7].

Filter cakes formed by CB slurries do not have the same properties as those of bentonite slurries, yet still serve to support the excavation. A CB filtrate cake can have a permeability orders of magnitude higher than bentonite (i.e., $1\text{-}4\times10^{-7}$ cm/sec), and filter losses around 20 times as large [7]. This is due to the calcium in the cement causing flocculation and aggregation of the bentonite. Excessive filtrate loss can cause problems with the excavation by thickening the slurry (by dewatering through filtrate loss) and by lowering the level of slurry in the trench.

Set times for the slurry can be controlled to some extent by controlling the amount of cement, and through addition of additives. Rapid set times, however, are more easily achieved than retarded set times. The additives used most successfully are ground blast furnace slag and fly ash, which replace a portion of the cement in the mixture. Slag has been shown to reduce cut-off permeability, bleed water, slurry shear strength, and set time. Fly ash can aid in resistance to chemical attack and can increase set time and bleed resistance [7]. Another method used to reduce bleed water from the curing slurry, is to ensure that the slurry is mixed in a high shear mixer starting with a fully hydrated bentonite slurry [7].

Self-hardening (CB) slurries can offer a number of advantages in wall construction. This method is well suited for situations where the trenched material is unsuited for use as backfill or where there is insufficient area for SB backfill mixing. Also, because the slurry hardens in place, the wall can be built in sections or panels (by excavating a tie-in between completed sections). This method allows for more flexible construction schedules, and can be used in more extreme topography [8]. Some disadvantages of this methods include the need for a greater amount of more expensive slurry, a relatively higher permeability than SB walls, less resistance to chemical attack, and in contaminated environments, the need to dispose of contaminated trench spoils [8].

COMPATIBILITY

The presence of organic or inorganic compounds in the groundwater can have a detrimental effect on the bentonite slurry used during wall construction as well as the ability of the finished wall to contain pollutants. These chemicals can affect the physical/chemical properties of the bentonite and the backfill material, and can lead to failure of the wall either during construction or during its operational lifetime. Thus, before a slurry wall is conidered as an appropriate remedial response, the effects of the leachate on the bentonite slurry and on the finshed wall must be determined through testing. This testing procedure will provide the information that is necessary to select the proper grade of bentonite and the type of backfill material that should be used in construction of the slurry wall.

The following outlines the types of effects that chemical have on bentonite and backfill material, and the laboratory tests that should be conducted in order to establish the potential effectiveness of the slurry wall.

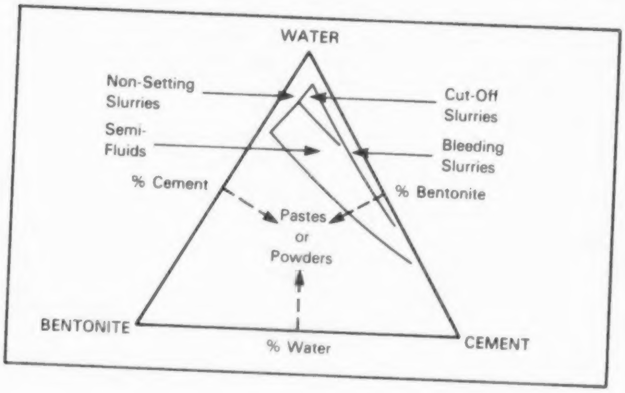

WATER
Non-Setting Slurries
Cut-Off Slurries
Semi-Fluids
Bleeding Slurries
% Cement
% Bentonite
Pastes or Powders
BENTONITE
% Water
CEMENT

Figure 5. Cement-Bentonite Slurry Compositions

(After Jefferis, 1981)

Chemicals can affect the physical and chemical properties of the bentonite and backfill material, leading to:

- Flocculation of the slurry
- Reduction of the bentonite's swelling capacity
- Structural damage to the bentonite or other backfill material.

In general, flocculation of the bentonite slurry can be caused by chemicals, such as electrolytes and metals, that act to reduce the natural repulsive forces between the hydrated clay particles. From a practical standpoint, the exact mechanisms are unimportant. However, if the slurry in the trench flocculates, due to chemicals in the make-up water or the soil, it can lose its ability to support the trench, leading to collapse [9]. This problem can usually be avoided by adequate site investigation and testing.

Numerous organic and inorganic compounds can, through a variety of mechanisms, cause bentonite clay particles to shrink or swell. All of these mechanisms affect the quantity of water contained within the interspacial layers of the clay structure. Many chemicals can reduce the double layer of partially bound water surrounding the hydrated bentonite, thus reducing the effective size of the clay particles[10,11]. This effect can increase the permeability of the backfill. Proper testing and backfill composition however, can prevent reduced swelling from having a detrimental effect on the final cut-off by measuring the permeability increase caused by the reduced swell and designing the backfill to account for it [16].

Strong organic and inorganic acids and bases can dissolve or alter the bentonite or soil in the backfill material, leading to large permeability increases[10]. Alumina and silica, two of the major components of bentonite, are readily dissolved by strong acids or bases, respectively. For example, when four types of clay were exposed to acetic acid, significant soil piping was reported to be caused by dissolution of soil components by acid [11]. This led to a significant increase in permeability within the four clay types. Proposed backfill materials should be tested to determine whether their permeability is adversely affected by contact with leachates or groundwater from the proposed site. Materials suffering from a predefined significant adverse affect should be eliminated from consideration at the site.

Compatibility testing is done using actual site leachate or groundwater and the proposed slurry and backfill. The tests are not all standardized or applied throughout the industry. In general, the tests include:

- Apparent slurry viscosity
- Filter press test
- Permeability.

Viscosity testing indicates the ability or inability of the slurry to form a thixotropic gel in the presence of the contaminants. The filter press test gives a rough indication of the ability of the slurry to form a filter cake in a contaminanted trench. Together these tests can tell the design engineer whether problems with trench support might occur.

Permeameter tests of the proposed backfill mixture, using the site leachate as the permeant, are essential in determining the expected cut-off effectiveness. Following wall installation permeability testing of the actual backfill material can be used to see if the design permeability was achieved. Care must be taken in collection of the leachate to ensure that the samples used in the tests are representative of the site conditions.

SLURRY WALL APPLICATIONS

Slurry walls have been, and are being, applied to a variety of waste site situations. The composition, dimensions, and placement of the walls are, of course, designed on a site specific basis. As noted above, wall composition is dependent on a number of factors including site lay-out, site chemistry and strength requirements. The following is a brief discussion of the factors affecting wall dimensions and placement with respect to the sources of pollution.

The dimensions of a slurry wall are essential design parameters, especially for depth and length. Wall width is largely a function of the excavation equipment used, and generally ranges from 2 to 5 ft [10]. The depth of the wall is most dependent on the behavior of the contaminants and the site stratigraphy. In most situations, it is necessary to key the wall into a low permeability underlying strata (aquiclude) such as bedrock or a clay layer. In some cases, such as with methane, or immiscible fluids less dense than the groundwater, such as some petroleum fractions, (so-called "floating contaminants"), a "handing wall" can be used. Hanging walls are not keyed into an aquiclude but are placed only deep enough to intercept the top several feet of the water table, thereby allowing capture of floating contaminants [13].

The length and shape configurations of a slurry wall are largely dependent on the location of the pollution source and any resultant contamination plume, as well as the intended role of the wall. In general, a wall can be placed surrounding a source, or upgradient or downgradient from the source with respect to groundwater flow.

Circumferential wall placement is employed in situations where more complete containment is desired. As shown in Figure 6, the wall surrounds the source and prevents migraiton into and out of the site. Care must be taken to prevent wall destruction by thorough compatibility testing and/or by preventing contaminant-wall contact.

Upgradient placement can divert groundwater flow around a pollution source, thereby protecting that groundwater from contamination and reducing the amount and rate of leachate generation. Care must be taken in the design to ensure that groundwater does not flow around the wall ends or rise to overtop the wall. Where upgradient drains are included to divert groundwater flow around a contaminated area, the cut-off increases assurance that the hazardous waste site is isolated from adversely affecting water quality. Figure 7 illustrates upgradient placement and barrier drain combination.

Downgradient placement, shown in Figure 8, can be used in situations where the amount of flow into a source is very low. In this practice, the slurry wall serves to capture the contamination plume so that it can be collected (by wells or drains) and treated. Again care must be taken to ensure that contaminated water does not have a destructive effect on the wall (or is kept from contact with it), and that the contamination does not overtop the wall.

It should be noted that slurry walls are rarely the sole type of engineered remedial measures. Most often, additional measures such as extraction wells, leachate collectors, and surface seals are used in conjuction with slurry walls as part of the total remedial effort.

SITE CHARACTERIZATION

To design and install a successful slurry wall, extensive site characterization, especially with respect to subsurface conditions, is necessary. The following is a summary of the major site characteristics relevant to slurry walls.

Site investigations for construction projects are frequently accomplished in two phases, a preliminary phase, and a design phase. A preliminary investigation will reveal many of the physical constraints that would affect slurry trenching operations. Among the most important considerations are:

- o Topographic restrictions
- o Buried or overhead obstructions
- o Equipment access
- o Sufficient work area.

These factors, and their interrelationships must be identified and considered very early in the design phase. Additional, general information will be collected on the subsurface conditions, which will allow the design engineer to select the most likely construction method(s).

The in-depth or design phase investigation will be more involved and more narrowly focused, centering on developing design parameters. For slurry walls, the principal focus will be on complete geologic and geohydrologic and, in some cases, geophysical characterization of the site. This is accomplished through a series of soil borings, initially general in nature and becoming more detailed as variability and anomalies are assessed. Among the more important parameters

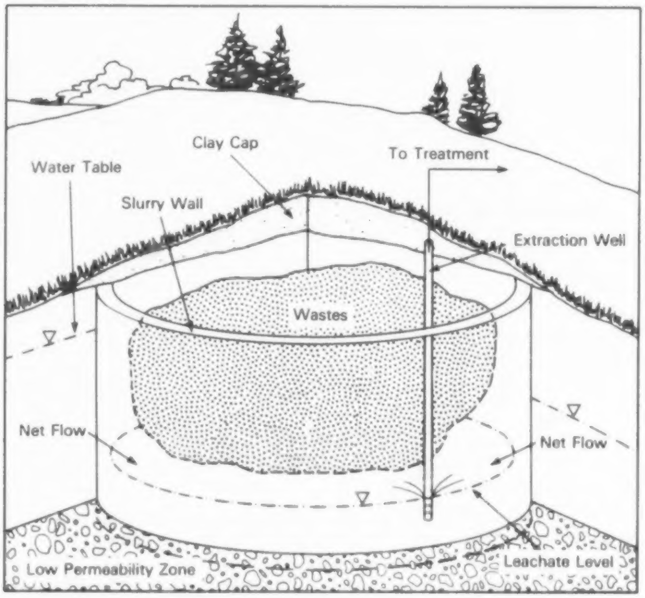

Clay Cap
To Treatment
Water Table
Slurry Wall
Extraction Well
Wastes
Net Flow
Net Flow
Low Permeability Zone
Leachate Level

Figure 6. Cut-away Cross-section of Circumferential Wall Placement

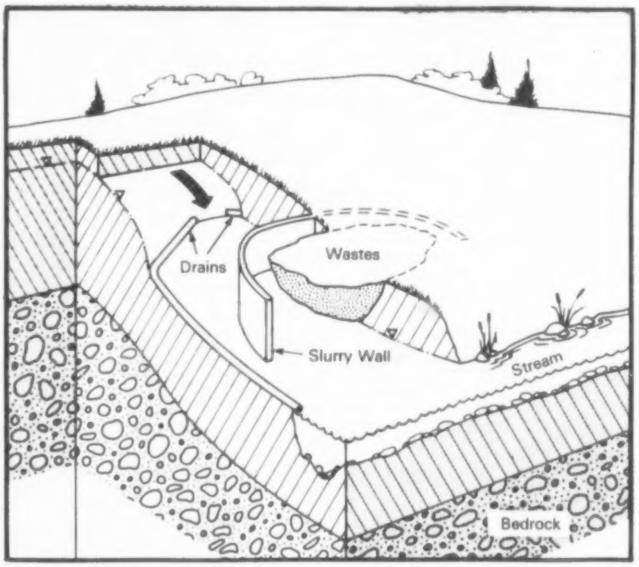

Drains
Wastes
Slurry Wall
Stream
Bedrock

Figure 7. Cut-away Cross-section of Upgradient Placement with Drain

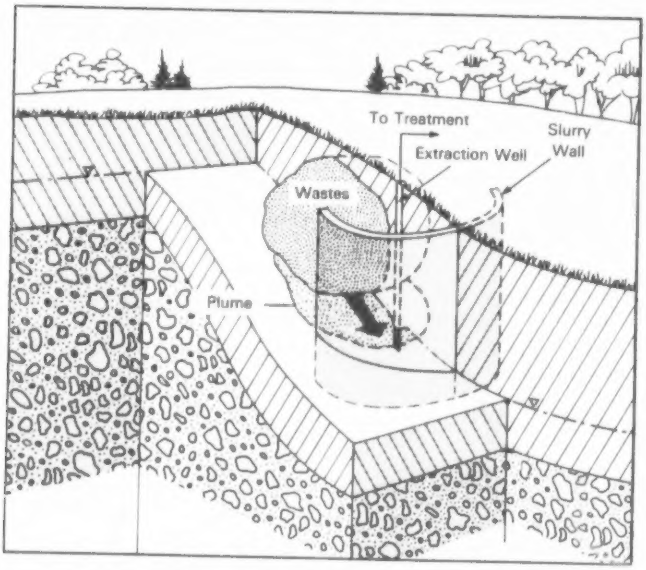

To Treatment
Slurry Wall
Extraction Well
Wastes
Plume

Figure 8. Cut-away Cross-section of Downgradient Placement

produced by this investigation are:

- o Soil distribution and nature
- o Aquifer geometry and gradients
- o Groundwater and leachate chemistry.

The accuracy and completeness of the design phase investigations are of prime importance to the success of a slurry wall project and should never be under estimated. Thorough site characterization can allow problems to be anticipated and planned for before they become detrimental to the project.

SLURRY WALL CONSTRUCTION

This section presents a general overview of the construction of a typical SB slurry wall. The major elements discussed are site preparation, excavation, slurry preparation and control, backfill mixing and placement, quality control, and cost.

The first phase of slurry wall construction is to prepare the site for work. This will vary considerably in nature and extent from site to site, but will involved such tasks as leveling the trench line, locating and/or moving overhead and underground obstructions, identifying storage areas and haul routes, and constructing impoundments for slurry hydration and storage. In cases where groundwater is very near the surface, a construction platform is often built along the trench so that the slurry can be kept well above the water table. Extra care in site preparation can help maintain construction schedules by identifying problems and planning for their resolution.

Excavation of the trench is accomplish using either a hydraulic backhoe or a cable or Kelly Bar mounted clam-shell grab. Backhoes are usually used for depths under 50 ft, however, in recent years, modified or "extended stick" backhoes have reached 73 ft. Below these depths, clam-shell grabs have successfully installed walls over 300 ft [13]. If a linear wall is being installed, backfilling can begin as soon as excavation has reached the point beyond the calculated backfill slope (see Figure 9). For a continuous, circumferential wall, however, the entire trench is often excavated before backfilling is begun.

Slurry is usually prepared on the site as close as practical to the trench. The bentonite is weighed and mixed with water in a high shear or venturi mixer. From the mixer, the slurry is pumped to a pond to circulate while hydration occurs. The hydration time is a function of bentonite quality, mixer shear, and pond circulation, and can vary considerably. From the hydration pond, the slurry is usually pumped to a storage pond before introduction into the trench. This procedure allows new slurry to be mixed and hydrated and provides a reserve supply of slurry in case the slurry level in the trench should drop suddenly when an unexpected pervious zone is encountered.

Most slurry trenching operations are accompanied by a simple mobile laboratory for testing new bentonite shipments, and for testing the slurry at various times during construction. The slurry is generally tested for viscosity (Marsh), density (mud balance), sand content, and pH. In many cases, filter loss and gel strength are also measured. Testing of the slurry is usually done after mixing, as it is introduced into the trench, and again as backfill is placed (a sample is taken from the trench bottom near the leading edge of the backfill). If the slurry in the trench is found to be too dense, additional new slurry is added to bring it back within specifications.

Backfill for a SB wall is usually mixed alongside the trench using a bulldozer. If additional soil or dry bentonite is needed it is spread evenly over the trench spoils and tracked and bladed with the bulldozer. During the mixing, slurry from the trench is added to the backfill mixture to form a homogenous, plastic paste [10]. When the backfill has reached the specified composition and consistency, it is ready to be placed in the trench.

Backfill placement is begun using a clam-shell grab to lower the backfill to the trench bottom. This continues until a slope of backfill extends to teh surface (see Figure 9). Thereafter, the backfill is pushed into the trench with a bulldozer and allowed to flow down the slope. In some cases, the slope may be established

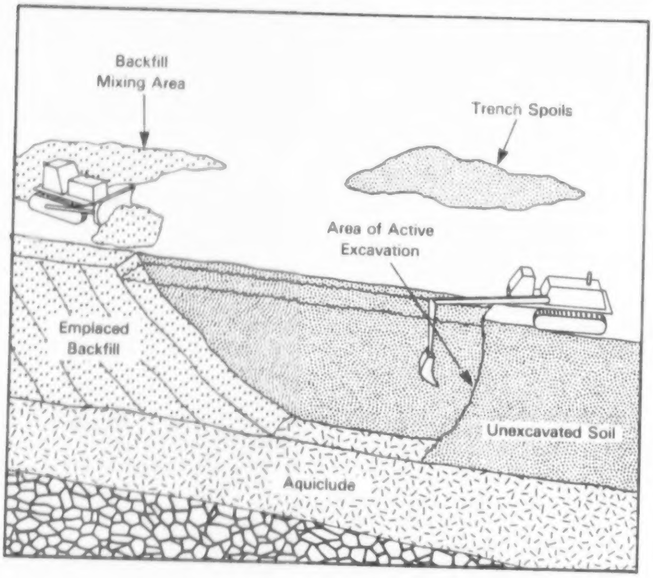

Backfill Mixing Area
Trench Spoils
Area of Active Excavation
Emplaced Backfill
Unexcavated Soil
Aquiclude

Figure 9. Cross-section of Slurry Trench, Showing Excavation and Backfilling Operations

by the excavation equipment, and initial backfill placement by a clam-shell is not required. If excavation and backfilling are well coordinated, the level of slurry in the trench should not fluctuate drastically.

As with any construction operation, slurry trenching requires that certain quality control procedures be followed. These procedures may differ from job to job, but are aimed at ensuring trench continuity (width and depth), backfill composition and placement, and slurry quality[8].

Trench continuity is extremely important to the finished wall because unexcavated material or improper key-in can greatly affect final permeability by leaving "holes" in the wall. This is mainly checked by observing the excavation operation and the material being brought to the surface. In shallow excavations, it is possible to sound the trench using a rod to "feel" for unexcavated material.

Quality control of backfill mixing and placement is second in importance to excavation but is essential nonetheless. Mixing is checked mostly by observtion but samples are taken for laboratory analysis at various times during the job to determine wheather they meet specifications. The control of backfill placement is focused on the slump of the initial backfill, and the slope thus formed. Care most be taken to ensure that no pockets of slurry are trapped in the backfill during placement.

Control of the slurry properties often receives the most attention, but is not of extreme importance to teh final wall. Control procedures, outlined above, center on ensuring that the slurry is of sufficient density to support the trench, but not so dense that it is not easily displaced by the backfill. Evidence indicates that as long as the slurry is at least 15 PCF less dense than the backfill, no problems should occur[2].

The cost of a complete slurry wall will vary a great deal depending on depth, ease of excavation, and materials involved. Table 2 shows the range of costs of SB and CB walls for different depths and media. Although the costs shown are in 1979 dollars, they remain valid examples. Decreases in the cost of bentonite, and increased excavation efficiency have offset inflationary increases.

CONCLUSIONS

The construction of cut-off wall barriers, using slurry trench techniques, to control the groundwater around landfill waste sites has enjoyed rapidly increasing popularity. This paper summarizes the "Technical Handbook on Slurry Trench Construction for Pollution Migration Control," which EPA's Office of Research and Development has prepared. It includes detailed discussions of the theory, design construction, and performance monitoring practices which are available within the engineering profession today.

Individuals within Federal, State, or local governments, or from private organizations who are responsible for reviewing the technical aspects of slurry trench cut-off walls for pollution migration control, can gain from this Handbook a familiarity with the site characterization, construction parameters, and performance expectations associated with these barriers. The evidence gathered to date indicates that a properly designed slurry wall, installed by a competent contractor, can be effective in long-term pollution control. Unfortunately, most of the slurry wall installations to date have been in the private sector and little objective monitoring data are available. Until such data are assembled and critiqued, it remains to be seen just how effective, and how long-term, this remedial measure is in controlling the spread of contaminated groundwater.

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3) LaRusso, R.S., "Wanapum Development Slurry Trench and Grouted Cut-Off," Grouts and Drilling Muds in Engineering Practice, Butterworth's London, 1963.

	SOIL-BENTONITE WALL			CEMENT-BENTONITE WALL		
	DEPTH ≤ 30 FEET	DEPTH 30-75 FEET	DEPTH 75-120 FEET	DEPTH ≤ 60 FEET	DEPTH 60-150 FEET	DEPTH > 150 FEET
SOFT TO MEDIUM SOIL N ≤ 40	2-4	4-8	8-10	15-20	20-30	30-75
HARD SOIL N 40-200	4-7	5-10	10-20	25-30	30-40	40-95
OCCASIONAL BOULDERS	4-8	5-8	8-25	20-30	30-40	40-85
SOFT TO MEDIUM ROCK N ≥ 200 SANDSTONE, SHALE	6-12	10-20	20-50	50-60	60-85	85-175
BOULDER STRATA	15-25	15-25	50-80	30-40	40-95	95-210
HARD ROCK GRANITE, GNEISS, SCHIST*	---	---	---	95-140	140-175	175-235

*NOMINAL PENETRATION ONLY

FOR STANDARD REINFORCEMENT IN SLURRY WALLS ADD $8.00 PER SQ.FT.
FOR CONSTRUCTION IN URBAN ENVIRONMENT ADD 25% TO 50% of Price

TABLE 2. Approximate Slurry Wall Costs As A Function Of Medium And Depth
(In 1979 Dollars Per Square Foot)
(After Ressi di Cervia)

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HANDBOOK FOR EVALUATING REMEDIAL ACTION TECHNOLOGY PLANS

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ABSTRACT

Remedial action technologies are designed to reduce human exposure to hazardous waste and decrease the contaminants to acceptable levels by either containing hazardous materials in place or removing the intrinsic hazard by decontaminating or physically removing the hazardous substances.

This paper discusses a document which provides an outline of technical information that potentially could be used to evaluate long-term remedial action plans for controlling or treating wastes or leachates at uncontrolled hazardous waste sites. The document, "Handbook for Evaluating Remedial Action Technology Plans", is not a design manual, nor does it contain rules or regulations pertaining to remedial actions. The intended audience includes those involved in the review of preliminary engineering reports or final design of remedial action at the waste sites.

INTRODUCTION

The development of remedial action plans and the ultimate implementation of those plans follows a series of steps set out in the National Contingency Plan (NCP)(1). Early in the process, alternative technological approaches are first identified and then screened through a net of increasing stringency regarding cost and effectiveness. The U.S. Environmental Protection Agency (EPA) has developed a substantial body of information on the various technological alternatives, most recently culminating in the publication "Handbook for Remedial Action at Waste Disposal Sites"(2). This Handbook contains extensive information about many potential technologies and is organized to assist planners and engineers in selecting or rejecting approaches.

As the plans evolve and get closer to implementation, they must be examined for technical and economic feasibility and conformance with the guidelines in the NCP. The evaluation process is carried out by many parties: the EPA, state agencies, responsible disposers and facility operators, and the public at large. This paper describes a complementary handbook (3) to the earlier publication that supports the evaluation process.

BACKGROUND

The Comprehensive Environmental Response, Compensation, and Liability Act of 1980 (CERCLA, also commonly known as Superfund), was passed late in 1981 to provide for (1) cleanup and emergency response for hazardous substances released into the environment, and (2) cleanup of inactive hazardous waste disposal sites. Section 105 of the Act directs the President to prepare a National Contingency Plan (NCP) to establish procedures and standards for responding to releases of hazardous substances. The NCP was required to include, among other things, methods for evaluating (including analyses of relative cost) and remedying any releases or threatened releases of hazardous substances, and means of assuring that remedial measures are cost effective.

After receiving comments on several drafts, EPA published the NCP in final form July 16, 1982 (40 CFR 300). The NCP describes procedures to develop and implement plans for remedying releases of hazardous substances. The NCP implements requirements in CERCLA and in the Clean Water Act (CWA).

The NCP process incorporates a number of judgments and decisions based on technical considerations. These judgments and decisions occur at several steps along the process and are made by the lead agency (EPA or a state depending on the existence and nature of the agreement between EPA and the state), private responsible parties developing remedial action plans, consultants and engineers supporting the above interests, and other interested parties.

The key parts of the NCP concerning remedial action are contained in Subpart F, which identifies the state role (Section 300.62) and a phased procedure for responding to the release of hazardous substances (Sections 300.63 to 300.70). Figure 1 illustrates the flow of the phases. The major focus of this report is on Phase VI - Remedial Action (Section 300.68). Figure 2 illustrates the Phase VI process in detail and indicates the steps associated with technical criteria for which the information in this document has been developed and organized.

The first several steps are designed to elucidate the nature of the problems at a site, to determine the major courses of action, and to develop a series of potentially cost-effective alternatives dictated by those actions. The latter steps, beginning with the initial screening of alternatives, are designed to select the cost-effective alternative using the set of criteria specified in the NCP.

The criteria include several that are related to technical features of the conceptual design in relationship to site-specific characteristics (the factors identified with an asterisk in Figure 2). Judgments as to the degree which proposed plans conform to the criteria must be based on project-specific designs and analyses. But there are a number of general, technology-specific data and engineering considerations which can be used to evaluate the plans, determine their appropriateness, and ensure that they have been developed from sound engineering principles using reasonable cost estimates.

More specifically, the report provides data to support the analysis and evaluation of:

- Feasibility, including:
    - acceptability (relevance to the particular project)
    - implementability or constructability
- Effectiveness, including reliability
- State of Development
- Cost

REPORT ORGANIZATION

The report includes a general discussion of remedial approaches to remedy problems in five environmental media:

- groundwater/leachate;
- surface water;
- soil;
- waste materials; and
- air.

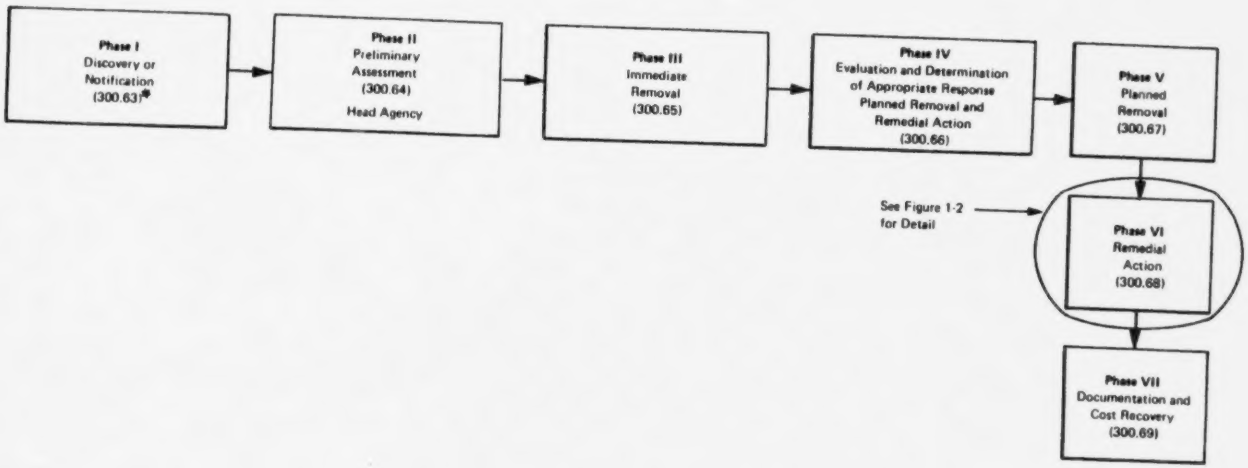
These categories are used to organize the discussions of 20 control technologies, i.e., remedial approaches to limit the extent of contamination and potential exposure and 28 treatment technologies, i.e., approaches that decontaminate the sources of potential exposure. Table 1 lists the technologies discussed in the report (3).

Each individual discussion includes highly summarized information on the items below:

- Description -- A brief, qualitative discussion of the technology and the principles on which it is based.

FIGURE 1

HAZARDOUS SUBSTANCE RESPONSE SEQUENCE (40 CFR PART 300)


Phase I
Discovery or
Notification
(300.63)*
Phase II
Preliminary
Assessment
(300.64)
Head Agency
Phase III
Immediate
Removal
(300.65)
Phase IV
Evaluation and Determination
of Appropriate Response
Planned Removal and
Remedial Action
(300.66)
Phase V
Planned
Removal
(300.67)
See Figure 1-2
for Detail
Phase VI
Remedial
Action
(300.68)
Phase VII
Documentation and
Cost Recovery
(300.69)

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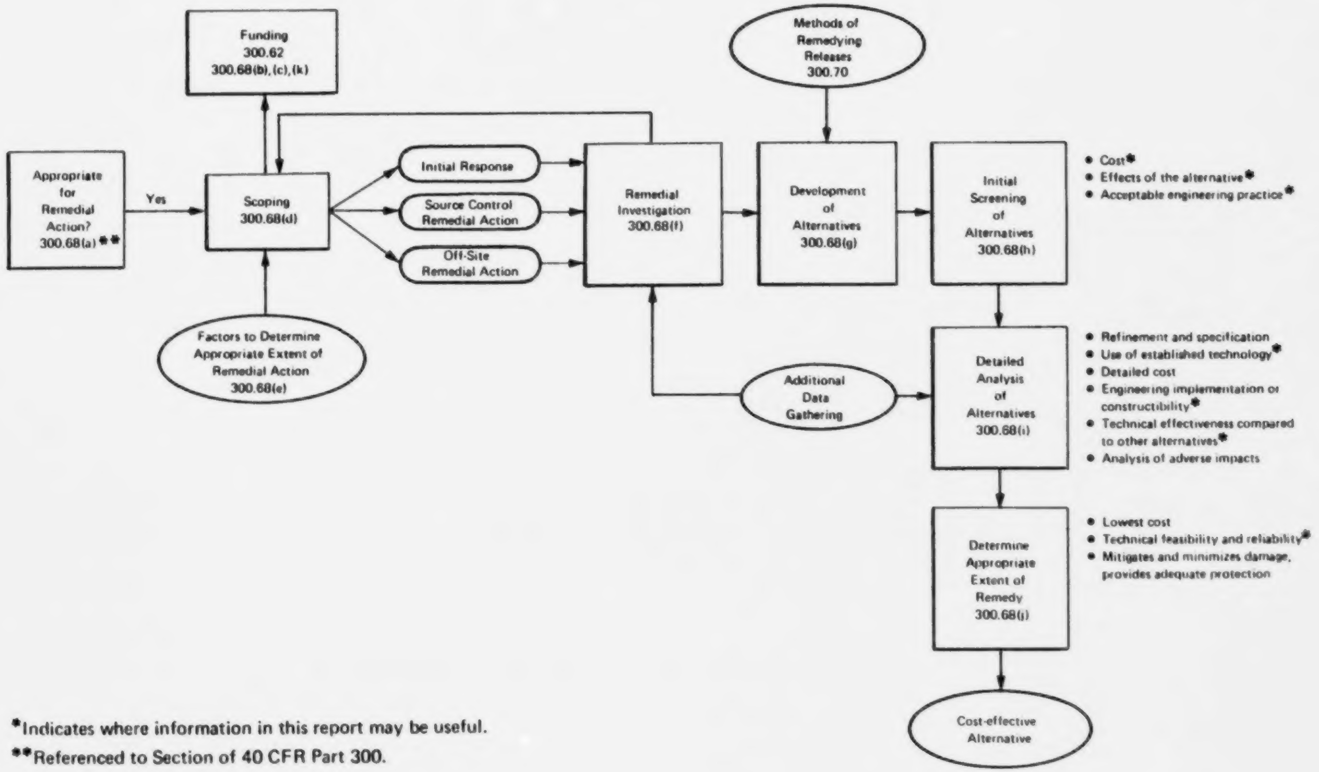
*Refers to the section of the NCP in 40 CFR part 300.

FIGURE 2

DETAILED SEQUENCE—PHASE VI—REMEDIAL ACTION (40 CFR PART 300.68)


Appropriate for Remedial Action? 300.68(a)**
Yes
Funding 300.62 300.68(b),(c),(k)
Scoping 300.68(d)
Factors to Determine Appropriate Extent of Remedial Action 300.68(e)
Initial Response
Source Control Remedial Action
Off-Site Remedial Action
Remedial Investigation 300.68(f)
Methods of Remedying Releases 300.70
Development of Alternatives 300.68(g)
Initial Screening of Alternatives 300.68(h)
• Cost*
• Effects of the alternative*
• Acceptable engineering practice*
Additional Data Gathering
Detailed Analysis of Alternatives 300.68(i)
• Refinement and specification
• Use of established technology*
• Detailed cost
• Engineering implementation or constructibility*
• Technical effectiveness compared to other alternatives*
• Analysis of adverse impacts
Determine Appropriate Extent of Remedy 300.68(j)
• Lowest cost
• Technical feasibility and reliability*
• Mitigates and minimizes damage, provides adequate protection
Cost-effective Alternative

*Indicates where information in this report may be useful.

**Referenced to Section of 40 CFR Part 300.

TABLE 1

REMEDIAL ACTION TECHNOLOGIES

CONTROL TECHNOLOGIES

GROUNDWATER CONTROL TECHNOLOGIES

- Slurry Walls
- Grout Curtains
- Sheet Pile Cutoff Walls
- Block Displacement
- Groundwater Pumping
- Subsurface Drains

SURFACE WATER CONTROL TECHNOLOGIES

- Dikes
- Terraces
- Channels
- Chutes and Downpipes
- Grading
- Surface Seals
- Vegetation
- Seepage Basins and Ditches

SOIL AND WASTE TECHNOLOGIES

- Excavation
- Drum Handling
- Encapsulation
- Dewatering

AIR CONTROL TECHNOLOGIES

- Pipe Vents
- Trench Vents

MONITORING TECHNOLOGIES

- Monitoring Wells
- Others Discussed

TREATMENT TECHNOLOGIES

BIOLOGICAL TREATMENT

- Activated Sludge
- Surface Impoundments
- Rotating Biological Discs
- Trickling Filters
- Land Treatment

CHEMICAL TREATMENT

- Neutralization
- Precipitation
- Reduction (For Cr)
- Wet Air Oxidation
- Chlorination (For Cyanide Only)
- Ozonation

PHYSICAL TREATMENT

- Reverse Osmosis
- Equalization/Detention
- Ion Exchange
- Carbon Adsorption
- Stripping
- Sedimentation
- Dissolved Air Flotation
- Filtration

DIRECT TREATMENT

- In Situ Leachate/Groundwater Treatment
- In Situ Physical/Chemical Treatment
- On-Site Physical/Chemical Treatment
- Solution Mining (Extraction)
- Biodegradation
- Solidification/Stabilization
- Incineration
- Thermal Oxidation Systems
- Carbon Adsorption For Air Emissions

- Status -- A measure of the availability of the technology and degree to which it has been demonstrated for hazardous waste remedial actions.

- Feasibility and Effectiveness -- A discussion of the technical factors important in understanding and reviewing the technology. This part gives background necessary for evaluating technology design plans and identifies areas of particular concern. For example, the effect of waste constituents on backfill and slurry materials is crucial to the effectiveness of a slurry wall. This part also contains a short discussion of special precautions to be taken in using the technology and any limitations of the technology being discussed.

- Design Basis -- This portion includes a summary of the major factors which determine the performance of treatment technologies. This part, which is unique to the treatment technologies is used to separate basic design information from the technical concerns of implementing leachate treatment technologies. Where possible, equations relating design parameters to desired performance and site conditions are provided in summarized form. Otherwise, the relationships are described in qualitative terms.

- Principal Data Requirements -- The principal site-specific data necessary for the design and evaluation of the technology are noted. The data noted must be obtained in the site investigation or in laboratory based studies.

The evaluation criteria or performance related factors most directly related to each major data requirement are noted. A summary of the data requirements common to all of the technologies is shown in Tables 2 and 3.

- Elements of Cost Review -- Information is provided for analyzing technology cost estimates. Each cost discussion is divided into three parts. Components lists the major components of cost, including those which involve initial construction and capital costs, and those which involve ongoing operation and maintenance (O&M) costs. Major Factors lists the characteristics of the technology as designed for a given site (e.g., size, material availability, pretreatment requirements) that most affect overall cost. Data provides information on unit and total costs associated with the technology. Cost data provided has been updated from available sources to 1982 dollars using several conventional indices.

EXAMPLE

The following example, on precipitation, a leachate treament technology, is adapted from the report to indicate the nature of the information included.

Precipitation

Description

Precipitation is a widely used (in industrial practice), relatively low-cost physical chemical technique in which the chemical equilibrium of a waste is changed to reduce the solubility of the undesired components. These components precipitate out of solution, as a solid phase, often in the form of small or even colloidal particles, and are removed by one of several possible solids removal techniques. Precipitation is most commonly used to treat heavy metals-containing wastes.

Status

Conventional, demonstrated.

Feasibility and Effectiveness

General Features

Precipitation is induced by one of the following means:

- adding a chemical that will react with the hazardous constituent in solution to form a sparingly soluble compound;
- adding a chemical to cause a shift in solubility equilibrium, reducing the solubility of the hazardous substance; or
- changing the temperature of a saturated or nearly saturated solution in the direction of decreased solubility.

Chemical additives are the most often commonly used. Typical reagents are:

- sodium hydroxide, sodium sulfate
- lime ($Ca(OH)_2$)
- Iron salts, iron sulfide, ferric sulfate
- phosphate salts (especially for heavy metals such as As, Cd, Cr, Cu, Hg, Ni, Pb, Zn)
- Alum ($Al_2(SO_4)_3$)

The theoretical removal limits for many metal species is very low, particularly with sulfide precipitants. Figure 3 shows theoretical curves as a function of waste pH. Some organic species--for example, aromatic compounds and phthalates--can also be treated. Removal in practice often is one to two orders of magnitude less than the theoretical limit. Complexing agents, such as cyanide or EDTA, compete with the precipitant and may hold the species in solution.

Conventional precipitation processes are performed in the following three steps:

1. rapid mixing of precipitating chemicals and wastewater;

TABLE 2

CONTROL TECHNOLOGY DATA REQUIREMENTS

● = Useful Data
◆ = Required Data

REMEDIAL ACTION	Geography			Geology					Soils										Climatology						Groundwater							Surface Water					Waste Description			Reg	Other
	Topography	Accessibility of Site or Materials	Vegetation Characteristics	Rock Type	Structural Characteristics	Thickness of Strata	Depth to Impermeable Strata	Hydraulic Conductivity	Type (Texture)	Grain Size Distribution	Compaction	Strength Properties	Erosion Potential	Moisture Content	Permeability	Porosity	Depth	Chemistry	Precipitation (rainfall parameters)	Evapotranspiration	Storm Characteristics	Wind Characteristics	Temperature	Air Quality	Depth to Watertable	Potentiometric Surfaces	Direction and Rate of Flow	Recharge Quantity	Aquifer Characteristics	Chemistry	Infiltration	Runoff	Depth of Flow	Drainage Area	Flood Characteristics	Sedimentation	Chemical Characteristics	Physical Characteristics	Disposal Practices	Regulations	Other
GROUNDWATER																																									
slurry wall	●	◆		●	●	●	◆	●	◆	◆	●	●		◆	◆	●	●	●	●	●					◆		◆		●	◆	●						◆		●	●	◆
grout curtain	●	◆		●	●	●	◆	●	●	◆	●			◆	◆	◆	●	◆	●	●					◆		◆		●	◆	●						◆		●	●	◆
sheet pile	●	●		●	●	●	◆	●	●	◆	◆				●	●	●	●	●	●					◆		●		●	◆	●						◆		●	●	◆
block displacement	●	◆	●	◆	◆	◆	◆	◆	◆	◆	●	◆		●	◆	◆	◆	◆	●		●				◆		◆		◆	◆	◆	●			●		◆		●	●	◆
pumping	●	●				●	◆	●	◆	◆	●			●	●		●								◆	◆	●	◆	◆	●	●						●		●	◆	◆
subsurface drains	●	●				●	◆		●	●	●			●	◆		●								◆		●		●	◆	●			◆			◆		●	●	
SURFACE WATER																																									
dikes – flood	◆	◆	●		●		◆	●	◆	●	●	◆	◆		●				●	●	●	◆			●						●	●	●	●	◆	●	●	●	●	●	
dikes – runoff	◆		●						●	●	●	●	◆		●				●	●	◆										●	◆	●	◆		●				◆	
terraces	◆	●	◆						●		●	●	◆		●				●	●	◆										◆	◆	●	●		●					
channels	◆		●	●					●	●	●	●	◆		●				●	●	◆										●	◆	●	◆		●				◆	
chutes and downpipes	◆	●		●									◆						●		◆											◆	●	◆		●				◆	
grading	◆	●	●	●					●		◆	●	◆	◆	●		●		●	●	◆	●									◆	◆				●	●	●	●		◆
surface seal	●	◆	●						◆	◆	◆	◆	◆	●	◆		●	●	◆	◆	◆	◆	●	◆							◆	◆			●		◆	◆	◆	●	◆
vegetation	◆	◆	◆						◆	◆	●		●	◆	●		◆	◆	◆	●	◆	●	◆	●	●					●	◆	◆	●		◆	◆	◆	◆	◆		◆
seepage basin/ditches	●		●	●			◆		●	●	●		◆		◆		●		●	●	◆				◆			●	●	●	◆	◆		◆	●	◆				●	◆
SOIL AND WASTE																																									
excavation	◆	◆	●	●			●		●	◆	◆	●	●				◆					●		●	●												◆	◆	◆		
drum handling	●	●										●	●		●		●				●	●	●	●													◆	◆	◆		◆
encapsulation		◆																																			◆	◆			◆
dewatering	●														●				◆	◆		◆	◆	●							●	●					◆	◆			◆
AIR																																									
pipe vents	●	●							●			●	●	●	◆	●	◆		●			●	◆	●	◆						●	●			●		●	◆	◆		◆
trench vents	◆	●					●		●			●	●	●	◆	●	◆		●			●	◆	●	◆						●	●			●		●	◆	◆		◆

After: Enos, 1980

TABLE 3

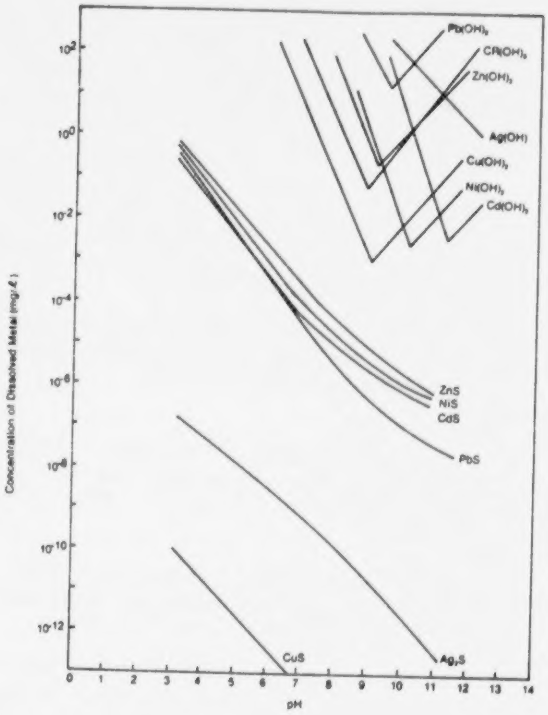
TREATMENT TECHNOLOGY DATA REQUIREMENTS

TREATMENT TECHNOLOGY	Volume	TKN	Flow	pH	Acidity Expressed as $CaCO_3$ Equivalent	BOD	COD	TOC	TSS	TDS	Metals	Cyanide	Temperature	Complexing Agents	Viscosity	Climate	Soil Permeability	Soil CEC	Oxidation Reduction Potential	Leachate Variability	Phosphorus Content	Particle Size of Suspended Solids	Presence of Interfering Species
Biological Treatment																							
Activated Sludge	x	x	x	x	x	x	x	x	x		x	x	x			x				x	x		x
Rotating Biological Disc	x	x	x	x	x	x	x	x	x		x	x	x			x				x	x		x
Trickling Filter	x	x	x	x	x	x	x	x	x		x	x	x			x				x	x		x
Surface Impoundment	x	x	x	x	x	x	x	x	x		x	x	x			x				x	x		x
Land Treatment	x	x	x	x	x	x	x	x	x		x	x	x			x	x	x		x	x		x
Chemical Treatment																							
Chemical Oxidation																							
Alkaline Chlorination	x		x	x	x							x											
Ozonation	x		x	x																			
Chemical Reduction	x		x	x							x												
Neutralization	x		x	x	x																		x
Precipitation	x		x	x					x	x	x	x		x									x
Ion Exchange	x		x	x					x	x	x	x											x
Wet Air Oxidation	x		x	x				x															x
Physical Treatment																							
Carbon Adsorption	x		x	x				x	x	x					x					x			x
Density Separation																							
Sedimentation	x		x	x					x													x	
Flotation	x		x	x					x													x	
Filtration	x		x	x					x													x	x
Reverse Osmosis	x		x	x					x	x					x					x			x
Stripping	x		x	x																			
Equalization/Dentention	x		x																	x			
In-Situ Treatment																							
Biological Methods	x		x	x		x	x	x					x			x	x	x					x
Chemical Methods	x		x	x							x					x	x	x					x

Figure 3.

SOLUBILITY OF METAL HYDROXIDES AND SULFIDES

(Source. Ghassemi, et al., 1981)



2. slow mixing of treated wastewater in a flocculation tank to allow settleable flocs to form; and

3. sedimentation of solids in a clarification tank.

The solids are removed by either:

- sedimentation, which separates the phases by the gravitational settling of the precipitate to the bottom of the sedimentation tank;
- filtration, which separates the phases by passing the precipitation effluent through a granular or cloth barrier, retaining the particles and allowing the clear effluent to pass through; or
- centrifugation, which separates the two phases in an enclosed vessel using certrifugal force to cause the solids to migrate through the liquid.

Special Precautions and Limitations

As noted, removal can be limited in the presence of complexing agents in the wastes. This problem can generally be eliminated by:

- using a sulfide precipitation agent;
- breaking up the metal complex by altering pH to either a basic or acidic extreme and adding a substitute cation to tie up the complexing agent when the pH is readjusted to precipitate the metal; or
- using insoluble starch xanthate as a precipitation agent (not widely used).

The sludge produced by precipitation should be considered hazardous unless laboratory tests show otherwise.

Design Basis

The major design factors are:

- effluent criteria;
- leachate flow; and
- concentration of precipitable ions in the leachate.

Based on the wastewater analyses and solubility curves for the species to be removed, laboratory tests are designed to determine optimum precipitation conditions and chemical requirements to satisfy effluent criteria.

A mixing tank is sized based on the leachate flow and precipitation chemical/leachate contact time required. Generally, contact time ranges from 10 to 60 minutes. Flocculation tank sizes are based on flow and retention time (typically 30 to 60 minutes). Clarification tank size is based on laboratory experiments to determine the settling rate and the leachate flow.

Principal Data Requirements

Leachate analysis (reagent choice, capacity);

- precipitable constituents;
- interfering species (i.e., cyanide, EDTA, etc.);

Leachate daily average and variation on flow (capacity);

Treatability study (capacity, reagent choice, and rate);

- optimum precipitation conditions;
- settling rate;
- sludge production rate;
- leachate flow;
- wastewater analyses of precipitable constituents;
- wastewater analyses for constituents that interfere with precipitation (i.e., cyanide, EDTA, etc.); and
- sludge production rate.

Elements of Cost Review

Components

Construction and Capital--

- tanks
- pumps
- mixers

O & M--

- chemicals
- electricity

Major Factors

- process volume

Data

Sample costs for several different capacity precipitation systems are given in Table 4.

ACKNOWLEDGEMENT

The preparation of this handbook was performed under Contract No. 68-01-5949 for the U.S. Environmental Protection Agency. The handbook will be available from the National Technical Information Service and the Solid and Hazardous Waste Research Division of EPA in Cincinnati, Ohio.

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3. EPA, Technology Transfer, 1983. "Handbook for Evaluating Remedial Action Technology Plans," In Press.

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TABLE 4
PRECIPITATION, FLOCCULATION, AND SEDIMENTATION COST ESTIMATES AS A FUNCTION OF SIZE

Basis: -Wastewater from Automotive Plating Operation
-Flowrate = 410,000 gpd, 350 day/year, 24 hour day
-Zinc Concentration = 113 mg/l
Capital Investment - $487,600

	Treatment System Size (Wastewater Flowrate)		
	82,000 gpd	410,000 gpd	2,050,000 gpd
Capital Investment	$171,700	$487,600	$1,388,300
Variable Cost			
Labor	72,400	109,800	165,100
Maintenance (4% Inv.)	6,900	19,500	55,500
Chemicals			
Quicklime	400	1,800	8,900
Coagulant Aid	1,400	7,300	36,300
Sulfuric Acid	220	1,100	5,500
Electrical Energy	1,200	6,000	29,800
Total Variable Cost	$ 82,500	$145,500	$301,100
Fixed Cost			
Capital Recovery	27,500	78,000	222,100
Taxes and Insurance (2% Inv.)	3,400	9,800	27,800
Total Fixed Cost	$ 30,900	$ 87,800	$249,900
Total Annual Cost	$113,400	$233,300	$551,000
Unit Cost ($/1000 Gal)	$ 3.95	$ 1.63	$ .77

Source: ADL, 1976

COLLECTION OF INFORMATION ON THE COMPATIBILITY OF GROUTS WITH HAZARDOUS WASTES

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ABSTRACT

This paper presents information on compatibility of grouts with different classes of chemicals. This information can be used for testing and selection of the type of grout to be utilized at a specific waste disposal site based on the compounds found in the leachate.

Twelve different types of grout are included in this study, based on their availability and utilization in waterproofing and consolidation projects. Sixteen general classes of organic and inorganic compounds are also identified that encompass the types of chemicals which could be found in leachate from hazardous waste disposal sites. The known effects that each of the chemical classes would have on the setting time and durability of each grout have been identified through an in-depth information search. These effects are presented in matrix form. Since compatibility data are not complete for each grout type, predictions based on reaction theory are made, where possible, for silicate and organic polymer grouts, to make information available on general compatibility trends.

The selection of a grout for a specific waste site will depend on its injectability, durability, and strength. These factors relate site hydrology, geochemistry, and geology to grout physical and chemical properties.

INTRODUCTION

Grouting is a technique by which a fluid material is pressure injected into soil or rock to reduce water movement and/or impart increased strength. Grouts accomplish this through their ability to penetrate soil voids and to gel or solidify in place. This technique has for many years been widely used for soil consolidation and groundwater control in tunneling, dam construction, and other building projects. However, its use at hazardous waste sites as a groundwater or leachate control measure has been limited. While all of the grout application techniques developed by the construction industry can be utilized at disposal sites, the ability of grouts to withstand the adverse chemical conditions found at these sites requires further investigation.

The types of application techniques that can be used at disposal sites include:

- curtain grouting,
- jet grouting,
- area grouting,
- contact grouting, and
- large void sealing (8).

All of these techniques can reduce water or leachate movement by reducing soil/rock permeability.

A grout curtain is an underground cut-off or barrier formed by injecting grout through grout pipes placed down bore holes in a specific pattern, typically in triple rows of primary and secondary holes. Starting with the primary holes, grout is injected in "pillows," working upward or downward in stages. This procedure forms rows of primary columns which, when set, are tied together by injecting the secondary columns (5). Figure 1 illustrates the wall or curtain formed by the coalescing columns.

Jet grouting is a method of cutting an opening in soil or soft rock using a high pressure nozzle (3). Once an opening has been made, using either water or grout as the cutting fluid, grout sets in the voids to form a low permeability zone. Using this technique, it is theoretically possible to emplace a grout liner beneath a waste site. Although this may require jetting through a hole drilled down through the wastes, advances in directional drilling techniques may soon make this method more practical.

Area grouting is a low pressure technique used to form a grout "blanket" in near surface soil materials. This is accomplished by injecting grout into a series of closely spaced injection holes placed in a grid pattern. This is usually performed to reduce infiltration, prevent erosion losses, or stabilize soils for heavy machinery bases (1). Area grouting may be adaptable to in situ waste immobilization depending on the compatibility of wastes with grouts.

Contact grouting is low pressure injection of grout to seal surface cracks or other voids. This technique may be used to patch cracked concrete in dams or dikes to reduce leakage, and to seal the sides of excavations to reduce water infiltration (1). Applications of contact grouting to long term waste site remediation are limited.

Grouts have long been used for sealing large voids in rock and other materials, mainly in conjunction with dam or tunnel projects (1). Adaptations of this method to waste disposal sites could include forming a tie-in between a cut-off wall and highly fractured or weathered bedrock or for sealing leaks in aquatards caused by exploration bore holes or improperly installed wells. Figure 2 illustrates the use of grout to key in the bottom of a cut-off wall.

While grouting is a well proven construction technique for groundwater control that can be applied to disposal sites, the extreme chemical conditions found at these sites could reduce the effectiveness of the soil seal. While a great deal of information has been published on the physical/chemical properties of grout, very little data are available on the effect of chemicals on grout performance. Consequently, this study centered on collecting, organizing, and analyzing existing published and unpublished information on the compatibility and durability of grouts with various classes of chemicals.

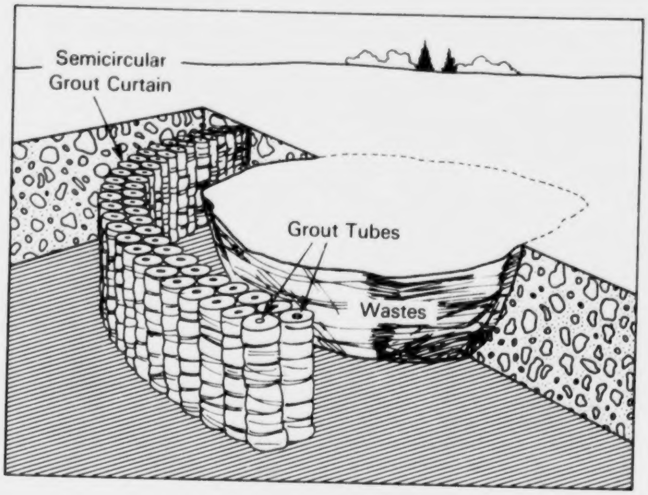
GROUT TYPES AND THEIR CHEMICAL INTERACTIONS

The grouts currently used for soil consolidation and groundwater control are particle suspensions, polymers, and emulsions. These materials are generally water-based solutions of sufficiently low viscosity to allow them to penetrate rock and soil voids.

Suspension grouts are the most common type of grout; they constitute approximately 95 percent of the grout used. Cement, clay, and clay-cement grouts are in this category. These materials are usually the more viscous of the available grouting materials and have the largest particle size. Thus, these grouts are best used in the grouting of rock or coarse material.

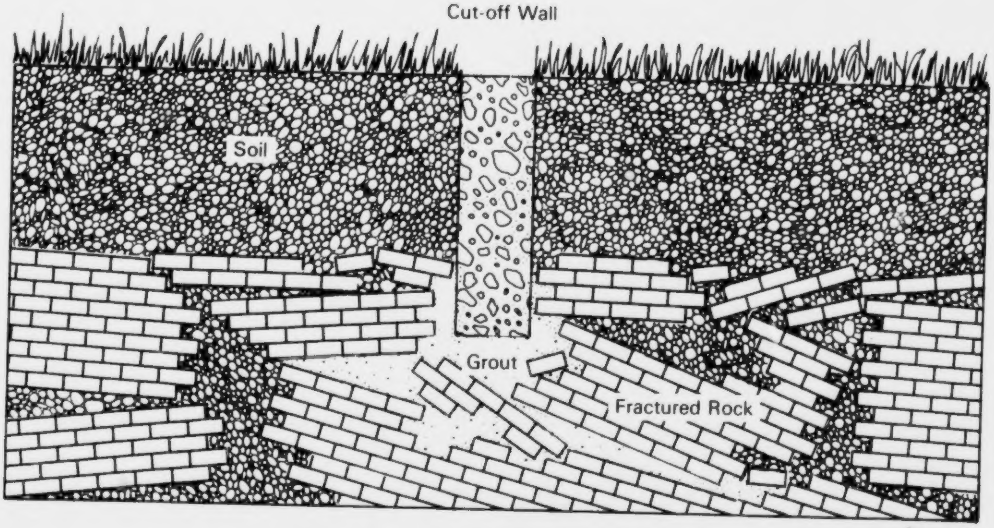
Polymer grouts represent almost 5 percent of the grout used. This class of grouts includes both silicate and organic polymer grouts with silicates constituting almost all of this category. Organic polymer grouts include acrylamide, urethane, phenolic, urea-formaldehyde, epoxy, and polyester grouts. Polymer grouts have low viscosities, initially, and thus can be used in fine grained, cohesionless soils, as well as for secondary treatment of coarse soils and rock fissures.

Emulsion grouts consist of either bitumenous emulsions or asphalts. These grouts can be used to seal soils, fill rock cavities, or construct thin cut-off walls.


Semicircular Grout Curtain
Grout Tubes
Wastes

Source: 9

Figure 1: Semicircular Grout Curtain Around Waste Site


Cut-off Wall
Soil
Grout
Fractured Rock

Source: 8

Figure 2: Bottom Key Grouting

However, they are limited in use.

Chemical interactions with grouts may be either positive or negative. Positive interactions tend to improve the characteristics of the set grout (e.g., decrease permeability, increase strength). Negative interactions will change the characteristics or behavior of grout such that it no longer fulfills its intended purpose which is to prevent migration of contaminants. These negative grout/chemical interactions take three general forms:

- prevent formation of grout matrix,
- destroy/interfere with grout matrix, and
- prevent sealing of grout with soil/rock.

Chemicals, as well as groundwater flow, can delay the set time of the grout such that a gel matrix never forms or is substantially weakened. Many of the grouts, particularly the organic polymer grouts, consist of several reactants as well as additives to catalyze or control the reaction rate. Any of these substances may preferentially react with chemicals in the groundwater (or leachate) as well as soil components. Such reactions can alter the set time of the grout through changing the mole ratio of reactants (by destroying reactive substances) or destroying additives that control the reaction and are generally present in very small quantities. In addition, the grout may be diluted by groundwater following injection and this can prevent gel formation in some grouts (e.g., phenolics).

Once the grout has set and the matrix has formed, chemicals may interact with the matrix in such a way that permeability increases. First, the grout matrix and its components can shrink or swell in reaction to chemicals as well as water. This swelling or shrinkage corresponds to water moving into or out of the matrix; such water movement can result in irreversible cracking of the grout which increases its permeability. The second interaction mechanism involves dissolution or leaching of grout matrix components which ultimately creates piping or channeling within the matrix and increases its permeability. This leaching may occur through hydrolysis of matrix components or through chemical dissolution (e.g., solvents dissolving bitumen). The third mechanism involves reaction of chemicals with the grout matrix components. Such reactions can destroy the matrix structure, thus increasing its permeability. For example, chemicals can react with polymer grouts to destroy either the polymer chains, the crosslinks between polymer chains, or both; as these bonds are broken, the polymer matrix is destroyed and chemical solutions may penetrate the grout.

Finally, chemicals in the soil can prevent formation of a seal between the grout and the soil or rock. Proper sealing may also be affected by dehydration of the grout. Dehydration can cause the grout to shrink from the surrounding soil or rock; this may also occur during setting or "drying" of the grout. In some instances this shrinkage is irreversible and permanent voids are formed.

GROUT/CHEMICAL COMPATIBILITY

Through a detailed evaluation of available information on the effects of chemicals on grout performance, a series of matrices were developed that summarize and define the compatibilities of grouts with various chemical groups. This information was gathered through contacts with representatives from universities, industries, trade associations, and government agencies along with a detailed review of the published literature sources which addressed not only grouting-related publications but also references on waste fixation/solidification, cement chemistry, landfill/lagoon liner performance, slurry wall construction, and polymer chemistry as well as performance specifications for cement, coatings, and tile grouts.

From the information obtained, three matrices were develped which summarize the known and predicted compatibilities of grouts with various chemical groups. These matrices provide a step-wise analysis of the data moving from general to specific information that has been found. It must be noted, though, that most of the information detailed the effects of pure chemicals or did not specify a concentration. While leachates generally contain low levels of compounds, there can be instances where grouts will come in contact with high concentrations of chemicals, such as organic solvent lenses within the groundwater system; thus, information on pure chemicals is relevant to grout/chemical interactions.

Chemical Groups

In order to address the types of chemicals that may come into contact with grouts used in a disposal site situation, the universe of chemicals was divided into 16 basic groups. The choice of these groups was not meant to be all inclusive but, rather, a representative choice of the types of chemicals which could be found in landfills. These chemical groups are as follows:

- o alcohols and glycols,
- o aldehydes and ketones,
- o aliphatic and aromatic hydrocarbons,
- o amines and amides,
- o chlorinated hydrocarbons,
- o ether and epoxides,
- o heterocyclics,
- o nitriles,
- o organic acids and acid chlorides,
- o organometallics,
- o phenols,
- o esters,
- o heavy metal salts and complexes,
- o inorganic acids,
- o inorganic bases, and
- o inorganic salts.

The organic categories were chosen by functional group or structural characteristic; the inorganics are essentially divided into the classical acid/base/salt categories. The functional grouping for the organics is useful because, although their physical properties and solubilities may differ, the interaction of the particular functional group with other groups remains the same. For example, all amines may not be soluble in water, but they all can be halogenated. In addition, one chemical may fit in more than one category if it has more than one functional group. For example, p-aminobenzoic acid is both an amine and an organic acid. The amine and acid moieties will chemically act independently of one another although the reactivity may be modified to some extent by the presence of the other group.

Known Compatibilities

Based on the information search, a matrix was developed which defines the known interactions between grouts and six general chemical classes: acids, bases, polar solvents, nonpolar solvents, heavy metals, and salts. Much of the available data on grout compatibilities refer to the effect of general classes of chemicals, such as salts or solvents, and not specific chemicals. This matrix, presented in Table 1, utilizes an alphanumeric compatibility index which shows the effects that a chemical class will have on the set time of a grout and its durability once it is set. The numerical portion of the index defines the effect that the chemical classes will have on grout set times, as follows:

1. no significant effect,
2. increase set time (lengthen or prevent from setting), or
3. decrease set time.

The alphabetic code relates to the durability of the grout in the presence of chemicals, as follows:

a. no significant effect,
b. increase durability,
c. decrease durability (destructive action begins within a short time period), and
d. decrease durability (destructive action occurs over a long time period).

A question mark on the matrices indicates where information is not available for one or the other of the codes, or both.

It should be noted that the matrix codes only address changes in set time or durability as a result of exposure to chemicals. The codes do not address the specific mechanisms that lead to changes in set time or durability nor do they address mechanisms other than chemical action. For example, bacterial action can destroy some grouts, thus the bacteria affect the durability of these grouts; this form of grout destruction is not addressed by the matrix.

Table 2 presents a more detailed matrix, where the chemical groups are more

Table 1: Interactions Between Grouts and Generic Chemical Classes

Grout Type / Chemical Group	Bitumen	Portland Cement		Clay (Bentonite)	Clay-Cement	Silicate	Polymers					
		Type I	Type II and V				Acrylamide	Phenolic	Urethane	Urea-formaldehyde	Epoxy	Polyester
Acid	?a	1d	1d	?c	?c	3a	2c	?a§	2c	1a	?a§	?d
Base	?a	1d	1a†	?c►	?d	2c	3d	?d	?d	2c	?a	?d
Heavy Metals	?	1a	?	?d	?	3?	3?	?	?	?	?	?
Non-Polar Solvent	?d	2c	2?	?d	?	?	?a	?d	?a	2?	?d	?d
Polar Solvent	?d	2c	2?	?d	?	?	?	?d	?a	2?	?d	?d
Inorganic Salts	?d	2c	2a	2d	?d*	3?	3d☆	3a	?d	?a	?a	?

KEY: **Compatibility Index**

Effect on Set Time
1 No significant effect
2 Increase in set time (lengthen or prevent from setting)
3 Decrease in set time

Effect on Durability
a No significant effect
b Increase durability
c Decrease durability (destructive action begins within a short time period)
d Decrease durability (destructive action occurs over a long time period)

* Except sulfates, which are ?c
† Except KoH and NaOH, which are 1d
☆ Except heavy metal salts which are 2
§ Non-oxidizing
► Modified bentonite is d
? Data unavailable

Table 2: Interactions Between Grouts and Specific Chemical Groups

Chemical Group \ Grout Type	Bitumen	Portland Cement		Clay (Bentonite)	Clay-Cement	Silicate	Polymers					
		Type I	Type II and V				Acrylamide	Phenolic	Urethane	Urea-formaldehyde	Epoxy	Polyester
Organic Compounds												
Alcohols and Glycols	?a	?d	?d	?d	?d	?	?d	?	3a	?	?a	?a
Aldehydes and Ketones	?d■	?	?	?d	?	?	?a	3a	?d	?	?	?
Aliphatic and Aromatic Hydrocarbons	?d	2a	2?	?d	?	?	?a	?d‡	?a	2a	?d	?d
Amides and Amines	?	?	?	?	?	?	?	?	3?	?	?	?
Chlorinated Hydrocarbons	?d	2d	2d	?	?	?	?a	?d	?a	2a	?d	?d
Ethers and Epoxides	?	?	?	?	?	?	?a	?	?a	?d	?	?
Heterocyclics	?	?	?	?d	?	?	?a	?	?	?	?	?
Nitriles	?	?	?	?	?	?	?	?	?	?	?	?
Organic Acids and Acid Chlorides	?a	1d	1d	?d	?d	?a	2a	?a	2a	1a	?d	?d
Organometallics	?	?	?	?	?	?	?	?	?	?	?	?
Phenols	?d	1d	?	?d	?d	?	?	2a	?c	?	?	?
Organic Esters	?	?	?	?	?	1a	?	?	?	?	?	?
Inorganic Compounds												
Heavy Metal Salts and Complexes	?d	2c	2a	?d	2c	3?	2?	?	?	?a	?	?
Inorganic Acids	?a§□	1d	1a	?c►	?c	3a	2c	?a§	2c	1d	?a§	?a✩
Inorganic Bases	?a	1a	1a†	?c►	?d	2c	3d	?d	?d	2c	?a	?d
Inorganic Salts	?d	2c	2a	2d	?d*	3?	3d	3a#	?d	?a	?a	?a

KEY: Compatibility Index

Effect on Set Time

1 No significant effect
2 Increase in set time (lengthen or prevent from setting)
3 Decrease in set time

Effect on Durability

a No significant effect
b Increase durability
c Decrease durability (destructive action begins within a short time period)
d Decrease durability (destructive action occurs over a long time period)

* Except sulfates, which are ?c
† Except KoH and NaOH, which are 1d
‡ Low molecular weight polymers only
§ Non-oxidizing
✩ Non-oxidizing, except HF
□ Except concentrated acids
■ Except aldehydes which are 1a
# Except bleaches which are 3d
► For modified bentonites, ?d
? Data unavailable

specific. The 16 chemical classes described previously are divided into two categories: organic and inorganic. This matrix provides a more detailed understanding of the types of chemicals that may have a detrimental effect on grouts. Like the general matrix, Table 2 does not contain any predictions or estimations of chemical/grout interactions. Only direct compatibility data are presented.

Predicted Polymer Grout/Chemical Compatibility

Because of the missing information encountered in preparing Tables 1 and 2, compatibility predictions were made for the silicate and organic polymer grouts. Other grout types were not evaluated due to the lack of information regarding their actual solidification chemistry. Predictions were made only where no data currently exist. The predictions are only indicative based on chemical structure and reaction chemistry. These predictions are the effects a chemical might have on a grout and do not necessarily represent the true field effects. Table 3 presents the matrix of predicted polymer grout/chemical interaction.

In order to make these predictions, a number of assumptions were made regarding the characteristics of landfills, groundwater/leachate, and polymer grouts. Landfills were defined as having the following properties:

- high salt content,
- organic compound concentrations around 1 percent, although some may be in the ppm range,
- metal ions individually do not exceed 1 percent, and
- pH ranges from moderately acidic (pH 3) to moderately basic (pH 11).

The groundwater may be considered a multicomponent dilute solution. It was further assumed that interactions between the components do not occur, but that interactions between the grout and each of the separate components may occur. These reactions were considered to be free of interference from the other components. Because groundwater has no turbulence and is slow moving, it is possible that chemicals which are insoluble in water may form a layer either on top or on bottom of the groundwater depending on their densities. Although these layers would be expected to be thin due to the low concentration of contaminants, the point of contact with the grout would be essentially "pure" contaminant, rather than a very dilute solution. This point of contact may then represent a special case and be a point at which an incompatibility may result in a critical weakening of the grout structure. For example, if a thin layer of organic solvents formed on top of the groundwater and the grout was solubilized or reacted with these solvents, the structure would be breached at that point. Once breached, the solvents could then penetrate more deeply resulting in a general weakening or alteration of the grout matrix.

One further assumption is made with respect to organic polymer grouts. The reaction of the organic polymer grout and its curing agent is not complete and a quantity of the unreacted polymer will remain. This assumption reflects the fact that even under highly controlled conditions, the stoichiometry of such reactions is ill-defined, and in a field situation, the conditions are not only uncontrolled but many times are undefined. The unreacted resins are assumed to be trapped in the polymer matrix with the reactive sites randomly oriented. These resins will appear on the surface as well as the interior of the grouting wall and will be available for reaction with chemicals brought into contact with the surface. A certain amount of migration from the interior to the exterior of the matrix is also expected to occur. Such migration is thought to occur slowly, so the possibility of reactions between the grouted structure and the surroundings may continue for an extended period of time. However, the predicted compatibilities are made for the totally reacted grout and do not take into account exposure of unreacted resins to the various chemicals.

The predicted grout/chemical interactions address a number of reactions between chemicals and grout constituents or the set grout. These interactions include:

- destruction of grout reactive components,

Table 3: Predicted Grout Compatibilities

Grout Type / Chemical Group		Polymers					
	Silicate	**Acrylamide**	**Phenolic**	**Urethane**	**Urea-formaldehyde**	**Epoxy**	**Polyester**
Organic Compounds							
Alcohols and Glycols	1a	1–	3b	–	1	1–	1–
Aldehydes and Ketones	1a	–	–	1a		1a	1a
Aliphatic and Aromatic Hydrocarbons	1d	1–	–	1–	–	1–	1–
Amides and Amines	3a	3d	3b	–a	1a	1a	3a
Chlorinated Hydrocarbons	1d	1–		1–	–	1	1–
Ethers and Epoxides	1a	1–	1a	1–		1a	1a
Heterocyclics	1d	1–	1a	1a	1a	1a	1a
Nitriles	1a	3–	1a	1a	1a	1a	1a
Organic Acids and Acid Chlorides	1–	–	3–	2–	–	–	1–
Organometallics	1a	3a	–	–	1a	1a	3► ?
Phenols	1a	1a	–	2–	1a	1a	1?
Organic Esters	–	?	?	?	?	?	1d
Inorganic Compounds							
Heavy Metal Salts and Complexes	–a	–	–	–	–	3–	3?
Inorganic Acids	–	–	2–	–	–	1–	1–
Inorganic Bases	–	–	3–	–	–	–	1–
Inorganic Salts	–d	–	–	–	–	–	3* –

KEY: Compatibility Index

Effect on Set Time

1 No significant effect

2 Increase in set time (lengthen or prevent from setting)

3 Decrease in set time

Effect on Durability

a No significant effect

b Increase durability

c Decrease durability (destructive action begins within a short time period)

d Decrease durability (destructive action occurs over a long time period)

* If metal salts that are accelerators

► If metal is capable of acting as an accelerator

? Data unavailable

- solubilization of grout, and
- alteration of grout structure.

Destruction of catalyst, activator, inhibitor, or other additives can inhibit polymerization and prevent proper setting of the grout. Chemicals in the groundwater may undergo reactions with major grout components that are competitive with the polymerization reaction; this may also delay or prevent setting of the grout.

Reactions of chemicals with the set grout can solubilize portions of the grout. Such reaction products may be soluble in water, organics, or both. Such dissolution can increase the permeability of the grouted area.

Chemical reactions with grouts and their reactants can alter the structure of the grout which in turn affects its stability and permeability. Ion exchange processes result in grout matrix components being replaced by substances in the groundwater. Such reactions can increase or decrease the crosslinking within the grout matrix. Similar results may occur through competitive reactions of chemicals with grout reactants. These reactions involve direct insertion of molecules into the grout matrix and can alter the matrix structure by creating voids in addition to altering the crosslinking which changes the properties of the grout.

GROUT SELECTION

The success of a grouting operation will depend on the selection of a proper grouting material for the specific area to be treated. The selection of a grout will not only depend on its compatibility with the leachate, but also on the physical/chemical properties of the grout and the geological characteristics of the site. If the grout is not able to penetrate the soil voids or does not possess enough strength to withstand the hydrostatic pressure present at the site, then its chemical compatibility is of little consequence. Thus, the properties of the grout must be matched with the geological properties of the disposal site. This can be accomplished by a step-wise analysis of three basic grout properties:

- injectability,
- strength, and
- durability.

By comparing each property to the conditions present in the geological structure, the proper type of grout can be selected. The steps in this selection process are illustrated in Figure 3.

Injectability

The injectability of a grout is controlled either by its viscosity or particle size. This property will dictate the grout's ability to penetrate a soil/rock structure. The lower the viscosity, the finer the voids that can be penetrated. Also, the smaller the particle size in suspension grouts, the smaller the voids that can be penetrated.

For all grouts, the closer the viscosity is to that of water (1.0 cP), the greater the penetration power. Grouts with a viscosity less than 2 cP, such as many of the chemical grouts, can penetrate strata with permeabilities less than 10^{-5} cm/sec. Higher viscosity grouts, like particulate and some chemical grouts with a viscosity greater than 10 cP, can only penetrate coarse strata having permeabilities greater than 10^{-2} cm/sec (7,4).

Strength

Once a grout has set in the voids in the ground, it must be able to resist hydrostatic forces in the pores that would tend to displace it. This ability will depend on the mechanical strength of the grout and can be estimated by the grout's shear strength (10). Shear strength of a grout will depend not only on its class, but also on its formulation. Thus, a class of grouts, such as silicates, can possess a wide range of mechanical strengths depending on the concentration and type of chemicals used in its formulation. The strength of the gel, then, can be adjusted, within limits, to the specific situation.

Durability

For permanent control of groundwater or leachate movement, the grout, once it is injected, must be able to set at the proper rate and, once set, not deteriorate over

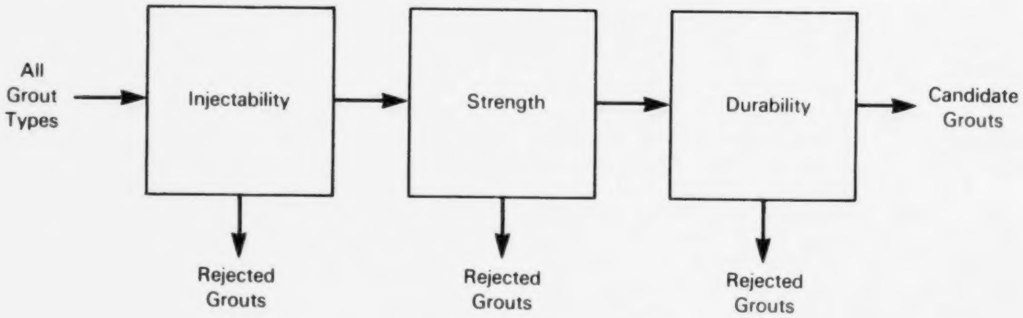

All Grout Types
Injectability
Strength
Durability
Candidate Grouts
Rejected Grouts
Rejected Grouts
Rejected Grouts

Figure 3: Grout Selection Process

time. The set time can be affected by a miscalculation of the grout's formulation, dilution of the grout by groundwater, being washed away in areas of high groundwater flows, or changes caused by chemicals contained within the grouted strata. Deterioration of the grout can be caused by water or chemicals structurally changing the grout. Also, removal of water from the grout matrix through dessication or syneresis can lead to shrinkage of the grout. All of these factors can weaken a grout leading to increased permeability.

Other Factors

Another grout selection factor that in some cases might be considered is the toxicity of the grout's components and the solidified grout. This factor will be important if the aquifer with which the grout comes in contact is a potential drinking water source. Both the chronic and acute effects of the compounds and the solidified grout must be considered.

The acute effects, as measured by oral LD_{50} values, have been determined for many of the compounds and set grouts. The values for set grouts are usually very high, for example over 15,000 mg/kg in laboratory rats for silicate grouts (10). The compounds used in formulating the grouts, though, usually have a lower LD_{50}, for example 150 mg/kg in laboratory animals for the acrylamide monomer (2).

The evaluation of chronic or long term exposure to the compounds used in grout and examination of the types of chemicals that could leach out of the set grout are current fields of investigation. Several of the compounds used in grout formulation, such as formaldehyde and toluene diisocyanate, could be potential carcinogens.

The cost of the grouting operation is also a relevant factor that can be considered in selecting grouting as an appropriate remedial action. This should include the costs of the materials as well as the injection costs. Current costs for grouted soils range from $\$100/yd^3$ to $\$500/yd^3$ of grouted soil, depending on the type of grout used and the characteristics of the soil (10).

CONCLUSION

While compatibility of a grout with the chemicals present at the disposal site is important, there are also a number of environmental and geological considerations that must be addressed in the selection process. All of these factors must be considered and any one could eliminate a grout from usage. Unfortunately, information on grout/chemical compatibilities is very limited and incomplete. The form or source of the available information did not allow for the evaluation of the testing procedures or the results. This led to conflicting data and incomplete information. As a result, the grout/chemical compatibility matrices cannot be used as a direct guide to grout selection, but instead provide information on the general compatibility trends and identify areas where more laboratory testing is needed.

ACKNOWLEDGEMENTS

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REMEDIAL ACTION RESEARCH: WASTEWATER LAGOONS

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Joseph R. Kolmer

ABSTRACT

Remedial action research at hazardous waste sites requires assessment of existing conditions and the design of a program which is effective in abating current contamination and preventing future releases. This paper discusses the efforts currently underway at the Louisiana Army Ammunition Plant (LAAP) to close two inactive wastewater lagoons. The lagoons consist of a small cadmium electroplating lagoon, and a pink water lagoon containing TNT-laden wastewater and sludge. Characterization of the site conditions is near completion, and laboratory evaluation of sludge and water treatment techniques is in the initial phases. Tasks within the research project include (1) treatment of the sludges, wastewaters and possibly soils to acceptable contaminant levels, (2) development of safe materials handling procedures for the TNT and RDX sludge in the pink water lagoon, and (3) long-term monitoring and evaluation of the effectiveness of the treatment procedures. Research activities are being closely coordinated with the U.S. Army Toxic and Hazardous Materials Agency.

INTRODUCTION

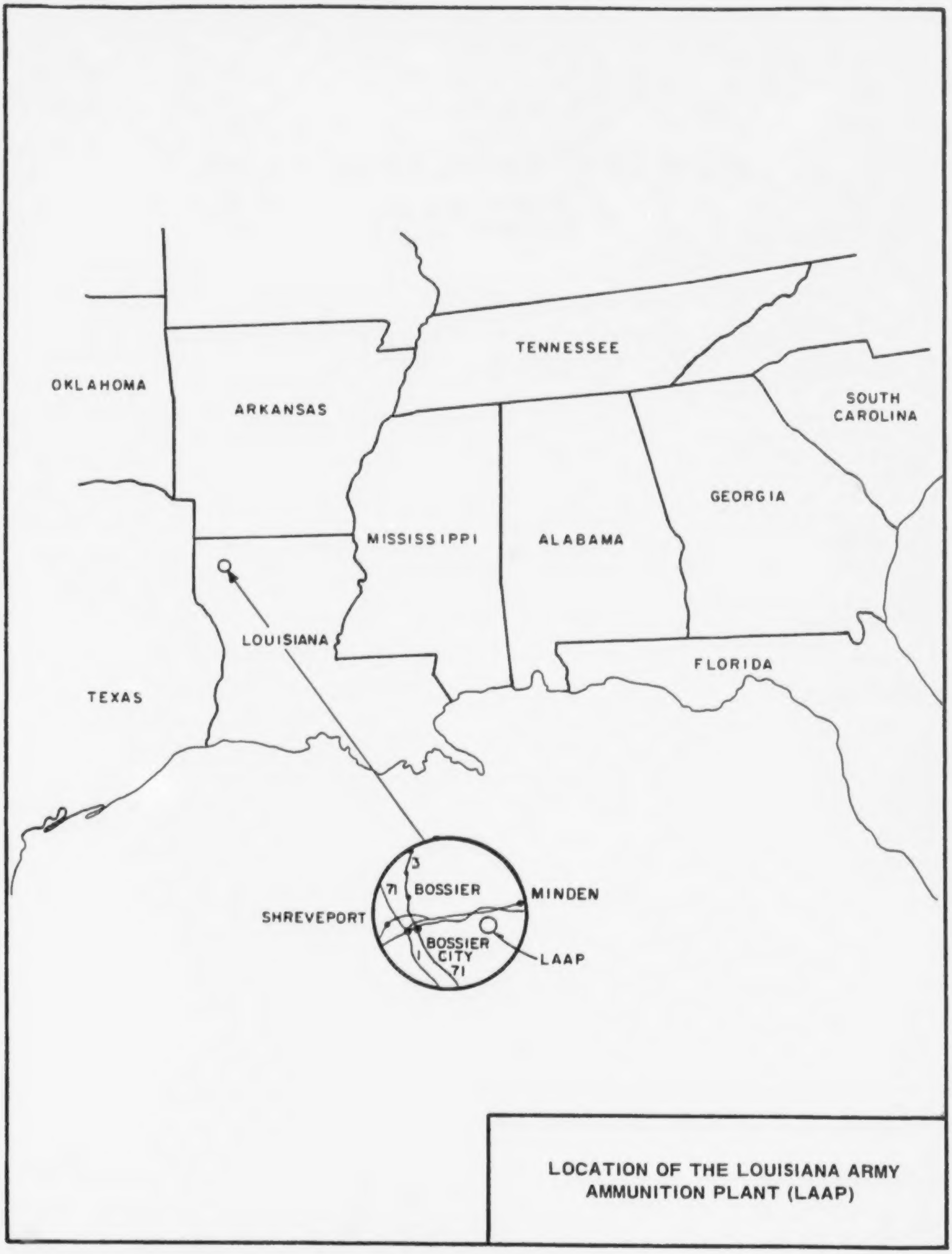
The principal goals of this research effort are to implement and assess the effectiveness of remedial actions at hazardous waste lagoon sites. Closure measures will be monitored at such sites in order to evaluate the effectiveness and appropriateness of site investigation techniques and closure methods.

Work to date on this project has included site investigations at an abandoned hazardous waste landfill (Kolmer, 1981) and at the inactive wastewater lagoons in an U.S. Army ammunitions packing plant. In addition, several methods of lagoon closure have been reviewed, and laboratory evaluations of some of these techniques are currently underway.

BACKGROUND

Site investigation activities related to the development of a remedial action research program are near completion at the Louisiana Army Ammunition Plant (LAAP), located east of Shreveport, La. (Figure 1). This work is being coordinated with the U.S. Army Toxic and Hazardous Materials Agency (USATHAMA). The lagoons to be closed at the LAAP site include a small electroplating waste lagoon, inactive since 1964, and a lagoon used for the disposal of 2,4,6-Trinitrotoluene (TNT) and Hexahydro-1,3,5-Trinitro-1,3,5-Triazine (RDX) contaminated process water ("pink water"). The principal effort in this research project will be directed to suitable closure and containment of the pink water lagoon, which is one of sixteen such lagoons at LAAP.

Groundwater quality analyses have been conducted in the area of the two lagoons by the U.S. Army Environmental Hygiene Agency (USAEHA, 1980). This program detected TNT, RDX and a number of other nitroaromatics near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LAAP

LOCATION OF THE LOUISIANA ARMY AMMUNITION PLANT (LAAP)

FIGURE 1

the pink water lagoons. Two monitoring wells were also installed in a clay stratum near the electroplating waste lagoon during the same drilling program. The concentration of metals near the electroplating lagoon in the groundwater was found to be within drinking water standards, except for slightly elevated levels of lead. The geologic units sampled are not used as a drinking water supply. No movement of contaminants beyond the property boundary has been detected in the wells south (downgradient) of the pink water lagoons.

SITE INVESTIGATIONS UNDER THIS RESEARCH CONTRACT

Field measurements of the thicknesses and volumes of sludge and wastewater in each lagoon were made to determine treatment volumes. These results are summarized in Table 1. It was found that the greatest thickness of sludge occurred very near the point of discharge of wastes into the lagoon, indicating a rapid settling of coarser particulates in the water. Concentration distributions of several of the contaminants in the sludges are similar to the sludge thickness contours, possibly indicating a preferential association of these compounds with the coarser particulates. Tetryl, RDX, and 2,4-Dinitrotoluene (DNT) show this type of distribution. The concentration of 2,4,6-TNT did not vary in a systematic manner with the sludge depths.

Chemical analyses of the groundwater, lagoon water, sludge, and soils underlying the lagoons were performed to identify the contaminants present, and to characterize certain parameters which could affect the treatment method employed. Some of these results are summarized in Table 2.

Soil samples were also collected from a soil boring near the electroplating lagoon, and from three shallow monitoring wells near the pink water lagoon. These samples were tested for geotechnical properties related to the remedial work. Soils near the electroplating lagoon consist of at least 7 meters of red clay to silty clay. Samples from the depth equivalent to the bottom of the lagoon contained cracks and slicken-sides which increase the permeability (as measured in the laboratory) to approximately 1.4 x 10^{-5} cm/sec. Immediately below this sample, the soil is similar, except that cracks were not observed and the measured permeability is approximately 5 x 10^{-8} cm/sec. Scarification and recompaction of the cracked surface clay should provide a suitable lining material for the disposal of the solidified sludge in the current lagoon area. Soils near the pink water lagoon consist of fine sands and silty clays. The geotechnical properties of these soils will be reviewed at a later date as part of the final remedial plan to determine their effect on the closure design.

Three monitoring wells, installed near the corners of the pink water lagoon, will be used for long-term monitoring of groundwater quality. Soil samples from beneath the

TABLE 1: APPROXIMATE VOLUMES OF SLUDGE AND WASTEWATER

Lagoon	Wastewater		Sludge	
	Volume	Depth	Volume	Depth
Electroplating	510 m^3 (135,000 gal)	1.4 m (4.5 ft)	59.5 m^3 (15,700 gal)	0.06 to 0.50 m (0.2 to 1.5 ft)
Pink Water	3550 m^3 (938,000 gal)	1 m (3 ft)	365 m^3 (97,000 gal)	0.06 to 0.90 m (0.2 to 4.5 ft)

TABLE 2: SUMMARY OF ANALYTICAL RESULTS, PINK WATER AND ELECTROPLATING LAGOONS

Parameter	Sludge	Soil Directly Beneath the Lagoon	Lagoon Water	Groundwater
Pink Water				
2,4,6-TNT	200 to 56,700 ppm	46.2 to 67.7 ppm	774 to 998 ppb	2900 to 6400 ppb
Tetryl	41.8 to 2100 ppm	NA	NA	NA
RDX	611 to 3740 ppm	NA	NA	NA
2,4-DNT	.825 to 40.1 ppm	.101 to .180 ppm	1.1 ppb	113 to 185 ppb
2,6-DNT	.106 to .901 ppm	.173 ppm	1.1 ppb	10 to 19.5 ppb
Nitrobenzene	1.090 to 9.14 ppm	1.78 ppm	11 ppb	11 ppb
1,3-Dinitrobenzene	.287 to 7.02 ppm	.290 ppm	1.8 ppb	135 to 173 ppb
Moisture[1]	49% to 92%	17% to 21%	NA	NA
pH	7.1 to 7.5	7.5 to 8.6	7.69	5.63 to 5.64
Reactivity	No	NA	NA	NA
Electroplating				
Cd, total	2300 to 9200 ppm	16 to 46 ppm	.016* ppm	.0045 ppm
Cr, total	7 to 1910 ppm	151 to 230 ppm	<.025* ppm	.026 to .074 ppm
Cu, total	27 to 244 ppm	0.3 ppm	<.025* ppm	.0068 to .0387 ppm
Pb, total	66 to 133 ppm	110 to 141 pm	<.20* ppm	.0204 to .147 ppm
Ni, total	37 to 1370 ppm	52 to 113 ppm	<.10* ppm	.0207 to .0741 ppm
Zn, total	181 to 5900 ppm	72 to 73 ppm	<.015* ppm	.0992 to .603 ppm
Moisture	46% to 58%	20% to 25%	NA	NA
pH	8.5	9.2 to 9.3	7.69	7.31 to 7.32

*Data from an analysis performed by the U.S. Army Environmental Hygiene Agency (May 15, 1981 correspondence).

NA: not determined

[1] % moisture = (g water/g sample) x 100

pink water lagoon are being subjected to a deionized water leaching procedure to assess the need to treat the soils along with the overlying sludge.

REMEDIAL ACTION AT THE ELECTROPLATING WASTE LAGOON

A number of different sludge treatment techniques were evaluated on a preliminary basis. Three of these processes were chosen for laboratory evaluation of the solidified sludge: Chemfix, Sludgemaster, and asphalt encapsulation. Splits of the same sample of the electroplating wastes were sent to the three vendors for solidification and preparation of proposals. Chemfix declined to bid on the project on the basis of information developed during this period. The Sludgemaster and asphalt encapsulated samples were analyzed for (1) total metal content, (2) leachate quality generated under the EP toxicity protocol, and (3) leachate quality generated using a deionized water leaching procedure (Battelle method). Results are summarized in Table 3. Both processes produced leachates of acceptable water quality. The Sludgemaster process was chosen on the basis of cost and time required to complete the solidification. Treatment of the water currently in the lagoon will not be required, since the water is of suitable quality for direct discharge.

It is anticipated that remedial action work at this lagoon will be implemented in January and February 1983. Subsequent work at the electroplating lagoon will consist of monitoring of the quality of the leachate generated in the field and comparing it with results from laboratory leaching procedures.

REMEDIAL ACTION AT THE PINK WATER LAGOON

The specific tasks required for achievement of the research objectives at the pink water lagoon include: (1) screening and handling or removal of the sludge from the lagoon, (2) treatment and ultimate disposal of the sludge, (3) monitoring/laboratory testing of the treated sludge and leachate, and (4) carbon treatment of the pink water and regeneration of the activated carbon using mobile units. Preliminary evaluation of techniques to achieve these goals has been completed. Previous research by USATHAMA and USAEHA (Wentsel et al. 1981, USAEHA, 1973) has been reviewed as part of this assessment. Three processes were chosen for further evaluation, as described in more detail below (Pink Water Sludge Treatment Options).

The final choice of the remedial technique will depend upon a number of considerations. As in the electroplating lagoon project, both deionized water and acidic leaching of the treated sludge will be carried out in the laboratory in order to evaluate the effectiveness of the treatment process. Deionized water is considered to be more representative of actual field conditions, while the acidic extraction (Toxic Extraction Procedure or TEP) is related to regulatory requirements for demonstrating the nonhazardous nature of the treated sludge with respect to drinking water parameters. Leachate quality will also be compared to current surface water discharge criteria for total nitrobodies to evaluate the effectiveness of the process in controlling leaching of the explosives and nitroaromatics.

Other selection considerations include the applicability of the technique to other wastewater lagoons, the feasibility of implementing and evaluating the method, the research benefit to be gained from implementation of the technique, lack of duplication of on-going USATHAMA research, costs, and the availability of mobile equipment.

In treating the sludge from the pink water lagoon, preference will be given to techniques which destroy the aromatic ring without the formation of undesirable by-products. Fixation or encapsulation processes which

TABLE 3: CHEMICAL ANALYSES OF SOLIDIFIED SLUDGE SAMPLES*

	As	Ba	Cd	Cr	Pb	Hg	Se	Ag
A. Asphalt								
1. Total Metals, Solidified Sample (ug/g)	< 1.8	87	551	50	33.8	0.64	< 0.4	< 0.4
2. E.P. toxicity								
a. Leachate concentration (ug/l)	< 54	4	19	< 9	< 39	< 25	< 66	< 8
b. % retained in solid	**	99.9%	99.9%	100%	100%	100%	**	**
3. Battelle (distilled water)								
a. Leachate concentration (ug/l)	< 54	43	10	< 9	< 39	< 25	< 66	< 8
b. % retained in solid	**	99.9%	100%	100%	100%	100%	**	**
B. Sludgemaster								
1. Total Metals, Solidified Sample (ug/g)	4.6	13.5	494	47.4	7.7	< 0.1	< 0.2	< 2.0
2. E.P. toxicity								
a. Leachate concentration (ug/l)	< 2	< 50	< 20	< 40	7	1.3	< 2	< 20
b. % retained in solid	**	100%	100%	100%	98.2%	**	**	**
3. Battelle (distilled water)								
a. Leachate concentration (ug/l)	< 2	< 50	< 20	< 40	7	0.9	< 2	< 20
b. % retained in solid	**	100%	100%	100%	98.2%	**	**	**
C. RCRA Leachate Criteria (ug/l)	5,000	100,000	1,000	5,000	5,000	200	1,000	5,000

* RCRA leachate criteria pesticides were below detection limits and are not included in the table

** not present in detectable amounts in solidified sludge

ND not detected

note: dilution ratio in leaching tests varied from 100 g/2 liters (EP tox) to 100 g/1 liters (Battelle) solely act to reduce leaching of the nitroaromatics would be considered only as a second choice. The processes currently under consideration for this lagoon include (1) an encapsulation process which evolves heat from chemical reactions, (2) thermoplastic encapsulation, to which heat may be added, and (3) biological degradation using mixed cultures or engineered microorganisms. These techniques will be tested on a laboratory and/or pilot scale prior to final selection and implementation. A more complete description of the sludge and water treatment methods is presented below.

PINK WATER SLUDGE TREATMENT OPTIONS

SLUDGEMASTER TECHNIQUE

Developers of this technique refer to the method as a "chem-thermo-coagulation" process. Heat is obtained from chemical energy released during the combination of premixed chemicals with the wastes, resulting in an increase in temperature and removal of substantial quantities of water in the form of steam. The treated wastes form a non-expansive material with low plasticity, high compactability and low permeability. The vendor has had experience in the treatment of a variety of organic and mixed wastes. Mobile equipment is available. This process will also be used at the electroplating lagoon.

General characteristics of this system are (1) the ability to process organics and wastes containing impurities (such as soil particles, waxes, etc.), (2) good leachate quality for the treated products of a wide variety of waste types, (3) the generation of high temperatures (> 200°F) and steam in the process, which may result in the destruction of the aromatic ring compounds (TNT, DNT, etc.) and (4) ready availability of mobile equipment and chemicals. Suitability, advantages, and disadvantages of this process at the pink water lagoon have not yet been evaluated. Such evaluation would involve laboratory analysis of the heat of reaction and chemical characteristics of the product material.

THERMOPLASTIC ENCAPSULATION

Coating of waste particles with asphalt or other thermoplastic materials has been used in the past, primarily for waste processing in the nuclear industry. In this process, the thermoplastic material is heated and mixed with the liquid or dry wastes using a twin-screw extruder or other mixing equipment. The extruder/mixer serves the dual purpose of reducing particle size of the wastes while mixing and coating it thoroughly with thermoplastic material. Coating of potentially explosive particles should reduce the propagation pathway of any explosive reaction which might occur in an individual particle. Similar extruder and mixer systems have been used successfully in the manufacturing of explosives. A number of vendors of the twin-screw extruders and mixers exist in this country.

If a twin-screw extruder is used, the temperature profile along the screws (several feet in length) can be closely controlled. The residence time in each section of the screw can be varied by changing the screw configuration and the speed of rotation. If a batch mixer is used, the operation may be stopped at any point to perform procedures such as the decanting of excess water. In either case, water and volatile organics are evaporated and collected in a condensor system or removed under a vacuum. The necessity for controlling any air emissions would be evaluated in the laboratory testing phase. The process generally results in a substantial volume reduction, due to the loss of water, and a product which is resistant to weathering and cracking.

Currently, an evaluation of the types of mixers and asphaltic material readily available on the market is being conducted. A broad range of asphaltic materials with different handling characteristics and physical properties (e.g. melting point, viscosity) are available. These characteristics are being matched with mixing equipment requirements in order to evaluate (based on published information) the optimum system for mixing, coating and heating the pink water sludge in a safe manner. This evaluation will be completed in January 1983 and a decision made as to any subsequent laboratory work. Phase two, if conducted, would consist of laboratory evaluation of the effectiveness of the system, safety, design of controls, and a differential thermal analysis of TNT breakdown temperatures.

Characteristics of thermoplastic encapsulation are (1) ability to process a very wide range of substances (limited only to corrosion and abrasion of the extruder), (2) good leachate quality of processed wastes, (3) the ability to reach and maintain high temperatures, with a high degree of control, and (4) successful use of the equipment in processing explosive compounds.

BIODECONTAMINATION

USATHAMA and others have conducted literature reviews and laboratory experiments related to the decomposition of TNT and RDX in biological treatment systems (Isbister et al., 1980, Osmond and Andrews, 1978, McCormick et al., 1981, Kaplan and Kaplan, 1982). Results indicated that, in one-step biological systems, RDX is degraded but the TNT ring either is not broken or forms undesirable by-products. It has been observed, however, that in the lagoons TNT tends to convert to other aromatics (such as 1,3,5 trinitrobenzene) which may be more readily degraded. A multi-step process, converting TNT to intermediates (trinitrobenzene, nitrobenzoic acid, etc.) which can then be degraded to CO_2 and water, has not been previously investigated. Formation of degradable intermediates may be feasible by using controlled chemical reactions, by mixed cultures of mutated microorganisms, or by alternating treatment conditions.

A substantial amount of research and field experience has been gained in the use of mixed microbial cultures (particularly in the degradation of spilled organics) since the publication of the USATHAMA research on TNT degradation. Mixed cultures may successfully result in biodecontamination by providing different strains for each reaction step in the process, where one type alone would not succeed. These cultures are developed using a combination of microbial mutation and selection of species which are able to survive by metabolizing the waste substrate.

A preliminary laboratory study is currently underway to study microbial breakdown of TNT. Agar plates are sprayed with extract from the sludge from the study lagoon and innoculated with either (a) soil microbes found at the LAAP TNT lagoons and cultured in the laboratory, or (b) a manufactured bacterial product (Hydrobac®) containing adapted mutant microbes with a capability for degrading a number of organic chemicals. Test conditions are described by the matrix in Table 4. Nitrogen starvation (all other nutrients supplied) will be tested in an effort to force the microbes to use the nitroaromatics as a nitrogen source. The pH 8.5 case is being evaluated since TNT is somewhat less stable chemically at higher pH levels. Normal pH and nutrient additions will also be assessed in case ideal conditions are needed to initiate and sustain growth until TNT degradation occurs. Toluene additions act to provide a cometabolite (i.e. a structure similar to TNT), which the microbes can adapt to more readily. Surfactant additions act to increase surface areas for microbial reactions.

At the end of a two week period, the plates will be inspected for microbial growth. Those showing significant growth will be analyzed for TNT degradation by comparing the extract from areas containing growth with no-growth areas of the same plate. If TNT loss is observed, a soil degradation experiment which more closely approximates field conditions will be implemented.

TABLE 4: AGAR TEST MATRIX, BIODEGRADATION STUDY

	NH_3-N Added		Nitrogen Starved	
	pH = 7.0	pH = 8.5	pH = 7.0	pH = 8.5
Hydrobac®				
Toluene	X	X	X	X
Surfactant	X	X	X	X
Field Culture				
Toluene	X	X	X	X
Surfactant	X	X	X	X

Characteristics of microbial systems include (1) reduced materials handling (in-place treatment may be feasible), (2) low costs due to low equipment costs and ease of operation, (3) high system mobility, and (4) lower volumes of by-products and residuals which must be landfilled (assuming complete degradation is possible).

MOBILE WATER TREATMENT SYSTEM

The mobile treatment system has been developed and will be operated by the EPA Oil and Hazardous Materials Spills Branch at Edison, New Jersey. The system consists of units for flocculation, sedimentation, filtration, and carbon adsorption. Depending upon the treatment requirements, contaminated water can be pumped into a settling tank where flocculation and sedimentation occur. The clarified fluid is then passed through multi-media filters before entering the carbon adsorption columns. Sludge is removed from the sedimentation tank and can be stored for treatment with the rest of the lagoon sludge. Treatment schemes can be varied as needed. If required, additional storage tanks are provided for filter backwashing or temporary storage of unprocessed materials.

The Mobile Physical-Chemical Treatment Trailer is mounted on a 13.7-m (45-ft) trailer and incorporates three multi-media filters, three pressure carbon columns (which may be used in parallel or in series), pumps, piping, controls, and a 100-kW diesel generator. A support trailer is equipped with additional pumps, fittings, and several collapsible rubber tanks, which permit the treatment trailer to be located up to 150-m (500-ft) from the lagoon. Contaminated water can be processed at flow rates up to 2,270 lpm (600 gpm).

MONITORING PROGRAM

The monitoring well network has been installed at the pink water lagoon, and will be used in conjunction with the previously installed wells to determine baseline conditions and water quality over a period of time. Leachate collection systems will be installed in both lagoons at the time of the treatment of the sludges. The leachate collection system at the M-4 lagoon will consist of a gravel blanket, sloped such that leachate can be collected in a sump at the low point of the disposal area. The pink water lagoon system will be designed after selection of the remedial technique.

Post closure monitoring of the effectiveness of the remedial action will continue for a period of three years. The design of the monitoring and analytical plans will be dependent upon the nature of the remedial plan implemented. Destruction of explosive and toxic compounds in the treatment process would reduce the amount of monitoring required at the pink water lagoon. In that case, effectiveness of the system will be evaluated primarily by laboratory analysis of the product for nitroaromatics and/or other toxic materials. The objectives and scope of testing will be formulated jointly by the EPA and U.S. Army.

SUMMARY

The LAAP project, currently in the laboratory evaluation phase, will provide information on site investigation techniques, remedial action implementation and long-term monitoring. Laboratory testing related to the pink water lagoon and implementation of remedial action at the electroplating lagoon will be completed in early 1983.

The long-term commitment at this site will allow the controlled installation of remedial measures and sufficient post-installation monitoring to adequately assess the performance of the entire remedial system. The controlled, rather than emergency, nature of these investigations will result in a more ordered and complete evaluation of the various aspects which must be considered in the closure of an inactive disposal site.

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A LITERATURE SURVEY OF THREE SELECTED HAZARDOUS WASTE DESTRUCTION TECHNIQUES

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ABSTRACT

In order to provide direction to the LSU Center for Hazardous Waste Research, a literature survey of current and proposed means for the destruction of hazardous wastes was conducted. As part of this study, three processes were identified as being applicable to spill and dump site wastes in which the wastes are present in concentrations in excess of 1 percent but are sufficiently dilute to preclude incineration without separation. These applicable processes, in-situ biological degradation, co-treatment in industrial facilities, and wet-air oxidation, are described and potential research areas to prove their viability are outlined.

INTRODUCTION

Largely neglected in the past, the problems of proper containment and/or complete destruction of hazardous chemical wastes have, in recent years, jumped to the forefront of the nation's environmental problems. The passage of a law creating the "Superfund" for hazardous waste cleanup, and the emotional response of the people affected by such contamination problems as Love Canal in New York, are indicative of the national concern over hazardous chemical wastes. As a response to these problems, the EPA has funded a significant amount of research into both fundamental and applied problems of waste generation, containment and destruction. As part of this research program, the EPA has funded the development of hazardous waste research centers at three universities. The newest of these centers is located at Louisiana State University, Baton Rouge, Louisiana. Each of the centers is charged with the responsibility of conducting the fundamental research necessary to support the development of hazardous waste control or destruction strategies. At this, the beginning of the second year of operation of the LSU Hazardous Waste Research Center, the specific direction this research effort should take are still under development. In order to provide a basis for selection of the center's direction or directions, a literature survey and analysis were undertaken whose objective was identification of the most feasible waste destruction processes and the research required to prove viability. At the outset, emphasis of this study was upon the ultimate disposal or destruction of hazardous waste rather than containment or separation. In addition, due to the expense and relative maturity of incineration processes, the emphasis of this study was on alternative (i.e., alternative to incineration) or novel means of waste destruction. This report is a summary of some of the results of this study.

Summarized in this paper are processes that exhibit, at least to the authors, significant potential for the disposal of wastes representative of spills or abandoned dump sites. Thus the waste will be assumed to contain a variety of chemical compounds at concentrations of a few percent. Incineration would be appropriate for concentrated wastes, while a variety of processes (see full report, [22]) would be appropriate for dilute wastes (taken to imply waste concentration <1%). This paper will identify destruction processes that can be employed on predominantly organic wastes in the intermediate concentration range.

The identification and assessment of individual processes were based on literature reports of existing research. A computerized search of NTIS, Chemical Abstracts, EPA documents, and other environmentally related databases was instituted, and appropriate book, journal articles or reports identified and read. In addition, potential processes were identified and discussed with the Chemical Engineering Faculty at LSU, as well as government and industrial visitors to the LSU Center for Hazardous Waste Research. Information was also gathered from papers presented and in discussion with conference attendees at the Cleveland and Los Angeles national meetings of the American Institute of Chemical Engineers.

As a result of these discussions and surveys, the following processes were judged to exhibit the most short-term potential for the destruction of spill and dump site wastes:

1) biological degradation via land treatment,

2) co-treatment of waste in industrial processes,

3) wet-air oxidation, including supercritical process.

Other processes investigated which were judged appropriate for some waste types included UV-assisted ozonation, chlorinolysis, microwave destruction, and molten sodium destruction. Due to physical and economic limitations on production of ozone, ozonation is apparently not a viable destruction means for wastes present at concentrations in excess of approximately 1 percent [4]. Chlorinolysis is applicable to halogenated wastes and apparently most appropriate as an end-of-pipe technology [4,18]. Microwave and molten sodium destruction of waste require significantly more research before their applicability can be proven but, at the present time, appear to be limited to small amounts of concentrated wastes [4,18].

BIOLOGICAL DEGRADATION VIA LAND TREATMENT

Land treatment, or soil incorporation, is an ancient method of soil fertilization [11], which is currently used to dispose of 25-30% of the sludge produced by municipal biological treatment processes [8], and perhaps as much as half of all refinery wastes [20]. The application of these techniques for the in-situ detoxification of a spill site has been investigated by Thibault and Elliot [19] and Johnson, et al. [7]. These investigators showed that degradation of the spilled chemicals is possible through application of the appropriate microorganism(s) and the necessary nutrients, and by providing aeration through plowing. The decomposition process is related to that which occurs in composting of wastes in piles, windrows or silos [4]. The appropriate microorganism can be selected on the basis of cataloged treatability [17], or developed for the specific waste by adaptation, mutation or genetic engineering [14]. The nutrients required include nitrogen and phosphorus, which are not normally available at sufficient concentrations at spill sites [19], and oxygen for the microorganisms through aeration. The significant advantages of land treatment of contaminated soils are summarized in Table 1.

Table 1. ADVANTAGES OF IN-SITU BIOLOGICAL DEGRADATION OF SPILL AND DUMP SITE WASTE

- No soil removal or transportation costs
- Minimal operation and maintenance costs
- Proven technology for municipal sludge disposal and other wastes

In order to apply land treatment techniques, however, several problems must be solved. The disadvantages or potential problems associated with the in-situ biological degradation of spill and dump site wastes are included in Table 2. Table 3 suggests appropriate research that may allow solution of these problems. Improvements in the rate and overall effectiveness of microbial destruction by genetic engineering is currently an active area of research [7,14,17,19]. Proper aeration of the soil is an important constraint on the

Table 2. DISADVANTAGES OF IN-SITU BIOLOGICAL DEGRADATION OF SPILL AND DUMP SITE WASTES

- Expenses of microorganism development (if required)
- Treatment time of weeks to months
- Generally incomplete destruction of the waste, especially for certain compounds
- Difficulty of effective soil aeration
- Requires containment of the waste during treatment
- Potential air emissions problem
- Public relations problems due to lack of an immediate response

Table 3. APPROPRIATE RESEARCH FOR IMPROVING IN-SITU BIOLOGICAL DEGRADATION OF SPILL AND DUMP SITE WASTES

- Investigation of methods for enhancing oxygenation of the soil (e.g. peroxide addition)
- Development of genetically engineered microorganisms suitable for rapid and complete destruction of the spilled compounds.
- Development of spill containment methods.

effectiveness of land treatment [19]. Recent research has indicated that hydrogen peroxide addition to the soil may provide an oxygen source without mechanical aeration [5]. Containment methods must eliminate ground-water contamination, leaching of the soil, and air pollution problems due to waste volatization [13,20]. This is a difficult problem in view of the length of time currently required to treat wastes via biological degradation. Resolution of these problems, however, will yield an effective means of destroying hazardous wastes without site removal.

CO-TREATMENT OF HAZARDOUS WASTES IN INDUSTRIAL FACILITIES

In an attempt to reduce the cost of separate treatment of hazardous wastes, co-treatment in industrial facilities has been suggested. The presumption is the through the appropriate choice of process and means of introduction, the wastes will be destroyed without significantly affecting the process. Such a waste destruction process would have the benefits listed in Table 4.

Table 4. ADVANTAGES OF CO-TREATMENT OF HAZARDOUS WASTES IN INDUSTRIAL FACILITIES

- Existing facilities
- Essentially complete destruction in appropriate process
- Potentially little effect on existing operation

Perhaps the best example of a co-treatment process is the burning of chemical wastes as fuels in cement kilns. Cement kilns (wet process) are designed to produce a calcium silicate based substance called "clinker". Typical operating conditions are a maximum temperature of 1400-1500°C, a solids residence time of 1-4 hours and a gas residence time of 10 seconds or more [10]. Under these conditions, volatiles in the slurry are driven off, pyrolyzed and then oxidized, and the remaining slurry dried and calcined. Calcination is a solidification process that occurs through heating without significant interaction with the gaseous phase [4]. Although basically an incineration process, cement kiln co-treatment is included here because the primary objective remains production of the clinker and not destruction of the wastes. Lauker [10] has indicated, however, that essentially complete destruction is possible due to the high temperatures and long residence times, and the heat of combustion may even result in a fuel savings to the kiln operator.

Although cement kiln waste destruction is the most studied process for co-treatment, other industrial calcination processes, such as the coking of heavy petroleum residues and tars, may be appropriate. Petroleum residue coking is conducted at 415-450°C and 3-6 atm during a semi-continuous process, delayed coking, and at 480-565°C and atmospheric pressure during fluidized bed coking [4] . The principal high-value outlet for coke is in electrodes for aluminum production, a use which requires low metals and sulfur content [21]. The destruction of hazardous wastes in refinery coking units may be limited by the low temperatures of the process and by the metals and sulfur content requirements of the product coke.

Another refinery alternative for co-treatment is hydrotreating or hydrofining. Hydrocracking is a high pressure (100 atm) and moderate temperature (300-400°C) process used to convert heavy gas oils into lighter, more valuable products (e.g. gasoline) [21]. Hydrofining describes a number of processes that are designed to hydrogenate, but not crack, organic feedstocks [21]. Its primary application is in the desulfurization, denitrogenation and demetalization of poor quality crude oils [1] and synthetic (i.e. coal and shale based) oils [12]. In many cases, synthetic crude oil poses many of the same fouling and pumping problems that are also posed by hazardous waste mixtures. It may prove necessary, however, to physically separate water and inert solids from the waste before introduction to the hydrotreating unit (which would also make incineration an appropriate destruction method).

Other co-treatment processes for specific waste streams have been suggested [4]. All of the possible co-treatment processes, however, have the potential disadvantages listed in Table 5. In order to offset these disadvantages, appropriate areas for future research are indicated in Table 6. It is believed, however, that the most substantial barriers to widespread use of co-treatment is resolution of the social and legal implications of third party treatment in facilities not specifically designed for wastes.

Table 5. DISADVANTAGES OF CO-TREATMENT OF HAZARDOUS WASTES IN EXISTING INDUSTRIAL FACILITIES

- Handling and transporation of wastes required
- Physical separation of waste may be required for a particular process
- Question of liability for waste in the event of accidents
- Little incentive for operators of existing facility
- Potential contamination of existing product

WET-AIR OXIDATION

One of the major costs of the incineration and co-treatment processes is for energy. This cost can be greatly reduced by not vaporizing the waste material, and by carrying out the reaction at reduced temperature. The wet-air oxidation process, or oxidation of organics by oxygen dissolved in water either at subcritical [15,16] or supercritical [2,9] conditions provides both of these reaction condition advantages. The subcritical conditions are typically below 300°C and 20 megapascals (MPa), while the supercritical reaction is carried out above 374°C and 22 MPa.

Table 6. APPROPRIATE AREAS OF RESEARCH FOR IMPROVING CO-TREATMENT OF HAZARDOUS WASTES IN EXISTING INDUSTRIAL FACILITIES

- Identification of appropriate processes for particular wastes
- Accurate assessment of destruction and/or conversion efficiency and associated pollutant emissions
- Identification of form and significance of product contamination in particular processes

The only reactant required, other than the waste itself, is air; and the only solvent, water. Thus no additional hazards are introduced in the treatment process. The advantages of this process are listed in Table 7, and the disadvantages in Table 8.

Table 7. ADVANTAGES OF WET-AIR OXIDATION OF HAZARDOUS WASTES

- Energy efficient - avoids phase changes
- Does not require additional chemicals
- Proven commercially - Zimpro process

Table 8. DISADVANTAGES OF WET-AIR OXIDATION OF HAZARDOUS WASTES

- Organics exhibit varying degrees of reactivity.
- Complete destruction requires substantial temperature and pressure, or catalyst.
- Unproven in three phase systems - air, water-organic, soil.
- Some compounds difficult to destroy.

As the current disadvantages of the process include incomplete destruction of daughter compounds and refractory materials [6], the reaction rates of these materials provide an active area for research [3]. Disposable catalysts and free radical production from the waste itself are possible solutions to this problem.

In the long run, the process must be applicable to destruction of hazardous waste from spill or dump sites. We envision contaminated soil being introduced directly into the process. The soil provides a third phase which complicates the process by adding a mass transfer step. The combined desorption-reaction problem should be an area of active research.

Appropriate areas of research for wet-air oxidation are summarized in Table 9. We believe this process has great potential for treatment of hazardous wastes at the site of a spill or dump. The detoxified soil would then be a more easily accepted material, whether it remains at the site or is transported to a new location.

Table 9. APPROPRIATE AREAS OF RESEARCH FOR IMPROVING WET-AIR OXIDATION OF HAZARDOUS WASTES

- Identification of reaction conditions necessary to achieve complete destruction of each type of waste
- Evaluation of non-thermal means of enhancing degradation rate or effectiveness, including addition of catalysts, oxidizing agents, or free-radical initiators
- Demonstration of oxidizing capability in the presence of an inert solid phase
- Fundamental investigation of mass transfer-reaction in three phase systems (solid-liquid-gas).

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DRUM HANDLING PRACTICES AT ABANDONED SITES

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ABSTRACT

The objectives of this project are to document drum handling techniques, identify research and development needs, and develop new or improved techniques. The aspects of drum handling that were addressed include the following: detecting and locating drums; determining drum integrity; excavating and staging; segregation by waste type; consolidation or overpacking; temporary storage and shipping and decontamination. A number of approaches or combination of equipment and techniques are applied to a site based primarily on considerations for safety of field personnel, potential for uncontrolled releases of wastes, site specific factors affecting equipment performance and costs for alternative approaches.

INTRODUCTION

Land disposal of drums containing hazardous wastes has been a widespread practice throughout the United States. Many problems at abandoned waste disposal sites have been attributed to drum disposal. The results of a 1980 survey of remedial actions at 169 sites conducted by the United States Environmental Protection Agency (USEPA) indicates that about one quarter of all abandoned sites have major drum related problems[1].

Past drum disposal practices have resulted in many instances of groundwater, air, soil and surface water contamination. At some sites explosions and fires have resulted from reactions of incompatible wastes which leaked from drums.

The cleanup of waste sites containing drums poses several hazards to field workers and to the environment. In many instances the integrity of the drums is poor and they are prone to rupture and leakage. The drum contents are frequently unknown and it is not unusual to find drums containing incompatible wastes in the same pit or trench. The hazard of cleaning up these waste drums is exacerbated in many instances, by the unsuitable site conditions in which they are found. Drums containing hazardous wastes have been found in a variety of environments including wetlands; the banks of rivers and streams; and highly industrialized, confined areas.

Because of the safety and environmental hazards involved in handling drums and the widespread efforts currently underway to clean up hazardous waste sites, the USEPA Solid and Hazardous Waste

Research Division has undertaken a research effort to evaluate drum handling practices and improve upon the existing equipment and methods where safety and effectiveness are seriously lacking.

As a means of documenting the state of the art and identifying research needs, a manual reviewing the applicability, advantages and disadvantages of equipment and methodologies for handling drums was developed[2]. This manual addresses the following activities:

- o Detecting and locating drums
- o Determining drum integrity
- o Excavation and on-site transfer of drums
- o Recontainerization and consolidation
- o Storage and shipping.

The selection and implementation of equipment and methods for handling drum related problems is made on a site-specific basis. Site-specific factors which affect the suitability of various equipment and methods include: the number of drums present at a site, depth of burial, accessibility of the site, integrity of the drums, site drainage, and types of waste present.

The typical sequence of activities involved in a site cleanup operation can logically be divided into five phases:

I. Preliminary Site Assessment
II. Field Investigation and Drum Detection
III. Development of a Cleanup Strategy
IV. Site Cleanup
V. Temporary Storage and Transportation

The drum handling manual focuses on equipment, methods and protocol that are used for activities undertaken during Phase III through V. Phase I, the Preliminary Site Assessment is generally completed by the time the drum handling operation begins and is not considered in detail. Nevertheless, the cleanup contractor, and Federal and state officials will need to draw on information gathered during this phase to reduce safety hazards and the cost and time required for subsequent activities. Background data on the site can often provide a great deal of insight on the types of wastes, condition of the drums and site specific variables which will influence the selection of equipment.

As with Phase I, Phase II, Field Investigation and Drum Detection, relies upon a considerable amount of field work that has generally been completed by the time the drum handling operation is begun. Drum detection using aerial photography, geophysical surveying and soil sampling are examples of activities that are conducted in Phase II.

Phase II, Development of a Cleanup Strategy, provides an overview of the four major variables which effect the selection of equipment and methods for handling drums·

- o Safety precautions
- o Protective and mitigative measures for environmental releases
- o Site specific conditions as they influence equipment selection and performance
- o Cost.

Phase IV considers equipment and methods for site cleanup after drum removal in terms of their applicability, safety, advantages, limitations and relative costs. Equipment and methods for temporary storage and transportation of wastes from drum cleanup operations are considered in Phase V.

The drum handling manual emphasizes both safety measures and measures for preventing or mitigating environmental releases. Tables 1 and 2 summarize these measures.

Although there are a variety of equipment types and methods available for handling drums at abandoned waste sites, there are several areas where the safety

Drum Handling Activity	Potential Safety Hazard	Safety Precautions
Locating Drums	Unknown location and contents of drums can lead to unsuspected hazards	• In conducting geophysical surveys, use hand held instruments rather than vehicle mounted systems where drums are close to the surface • Conduct soil sampling only after the geophysical survey is completed to minimize the possibility of puncturing drums • Use non-sparking tools for sampling • Use direct-reading, air monitoring equipment to detect hot spots where contamination may pose a risk to worker safety
Determining Drum Integrity	Process of visual inspections require close contact with drums of unknown content	• Any drum which is critically swollen should not be approached; they should be isolated using a barricade until the pressure can be relieved remotely • Approach drums cautiously, relying on air monitoring equipment to indicate levels of hazards which require withdrawal from working area or use of additional safety equipment
Drum Excavation and Handling	Exposure to toxic/hazardous vapors: rupture of drums.	• Where buried drums are suspected, conduct a geophysical survey before using any construction equipment to minimize the possibility of rupture • Use the drum grappler where possible and cost effective, to minimize close contact with the drums • If the grappler is not available, pump or overpack drums with poor integrity • Use non-sparking hand tools and non-sparking bucket teeth on excavation equipment • Where slings, yokes or other accessories must be used, workers should back away from the work area after attaching the accessory and before the drum is lifted • Critically swollen drums should not be handled until pressure can be relieved • Use plexiglas shields on vehicle cabs • Use "morman bars" which fit over the teeth of excavation buckets to prevent drum puncture

Drum Handling Activity	Potential Safety Hazard	Safety Precautions
Drum Excavation (Con't)		• Use direct-reading, air monitoring equipment when in close proximity to drums to detect any hot spots
Drum Opening	Release of toxic, hazardous vapors, rupture of drums	• Use remote drum opening methods where drums are unsound • Conduct remotely operated drum opening from behind a barricade, or behind a plexiglas shield if backhoe mounted puncture is being used • Isolate drum opening from other activities to minimize a chain reaction if an explosion or reaction did occur • Use only non-sparking hand tools if drums are to be opened manually • Remotely relieve the pressure of critically swollen drums before opening • Clean up spills promptly to minimize mixing of incompatible materials
Staging Recontainerization	Mixing of incompatible wastes	• Allow adequate spacing during staging of drums to provide rapid exit in case of emergency • Perform on-site compatability testing on all drums • Drums which are leaking or prone to leakage or rupture should be overpacked or the contents transferred to a new drum before staging • Clean up spills promptly to avoid mixing of incompatible wastes • Intentional mixing of incompatible wastes such as acids and bases should be performed under controlled conditions in a reaction tank where temperature and vapor release can be monitored • Monitor for hot spots using direct-reading air monitoring equipment
Storage and Transportation	Mixing of incompatible wastes	• Segregate incompatible wastes using dikes • Maintain weekly inspection schedule • Allow adequate aisle space between drums to allow rapid exit of workers in case of emergency
Storage and Transportation (Con't)		• Clean up spills or leaks promptly • Ensure adherence to DOT regulations regarding transport of incompatible wastes

TABLE 2. MEASURES FOR MINIMIZING ENVIRONMENTAL RELEASES DURING DRUM HANDLING

Potential Environmental Problem	Preventive Measures
Groundwater Contamination	• Improve site drainage around the drum handling area and minimize run-on and run-off by constructing a system of dikes and trenches • Where groundwater is an important drinking water source, it may be necessary to hydrologically isolate the work area using well-point dewatering • Use liners to prevent leaching of spilled material into groundwater during drum handling, durm opening, recontainerization and decontamination • Use sorbents or vacuum equipment to clean up spills promptly • Locate temporary storage area on highest ground area available; install an impervious liner in the storage area and a dike around the perimeter of the area; utilize a sump pump to promptly remove spills and rainwater from storage area for proper handling
Surface Water Contamination	• Construct dikes around the drum handling and storage areas • Construct a holding pond downslope of the site to contain contaminated run-off • Use sorbents or vacuum equipment to promptly clean up spills • Design the dikes for temporary storage area to contain a minimum of 10% of total waste volume; ensure that holding capacity of storage area is not exceeded by utilizing a sump pump to promptly remove spills and rainwater; for proper handling
Air Pollution	• Avoid uncontrolled mixing of incompatible wastes by 1) handling only one drum at a time during excavation; 2) isolating drum opening operation from staging and working areas; 3) pumping or overpacking leaking drums and 4) conducting compatibility tests on all drums.

TABLE 2. MEASURES FOR MINIMIZING ENVIRONMENTAL RELEASES DURING DRUM HANDLING (CONT'D)

Potential Environmental Problem	Preventive Measures
Air Pollution (Continued)	• Promptly reseal drums following sampling
	• Any drum which is leaking or prone to rupture or leaking, promptly overpack or transfer the contents to a new drum
	• Utilize vacuum units which are equipped with vapors scrubbers
	• Where incompatible wastes are intentionally mixed (i.e., acids and bases for neutralization) in a "compatibility chamber" or tank, releases of vapors can be minimized by covering the tank with plastic liner
Fire Protection	• Use non-sparking hand tools, drum opening tools and explosion proof pumps when handling flammable, explosive or unknown waste
	• Avoid uncontrolled mixing of incompatible waste by 1) handling only one drum at a time, 2) pumping or overpacking drums with poor integrity, 3) isolating drum opening, and 4) conducting compatability testing of all drums
	• Use sand or foams to suppress small fires before they spread
	• Avoid storage of explosives or reactive wastes in the vicinity of buildings
	• In a confident area, reduce concentration of explosives by venting to the atmosphere
	• Cover drums which are known to be water reactive

of the operation may be improved by additional research and development. As a result of discussions with cleanup contractors, equipment manufacturers, and EPA and state officials, additional research and development is recommended in the following areas:

- Remote drum opening methods
- Protocols for handling lab packs and gas cylinders
- Recommendations for minimum compatibility testing
- Inventory of major equipment used for drum handling
- Further evaluation of the use of non-destructive methods for determining drum integrity.

The next phase of this project will develop equipment to satisfy one or more of these needs.

DRUM HANDLING ACTIVITIES

Detecting and Locating Drums

Detecting drums at an abandoned site involves the use of historic and background data on the site, aerial photography, geophysical surveying and sampling. Background data should be carefully examined since it can minimize the cost and increase the safety of subsequent activities. Aerial photography involves the use of historic aerial photographs to show changes in the site over time, such as filling in of trenches, or mounding of earth. It also includes the use of current aerial imagery (usually color or infrared) to show spills, seepage or changes in vegetation which may indicate the presence of drums.

The applicability, reliability and cost effectiveness of geophysical survey methods are highly dependent upon site specific characteristics. Magnetometry is generally the most useful survey tool for detecting drums. Metal detectors may be of value if drums are close to the surface. Ground penetrating radar is extremely sensitive but is easily subject to interference. Electromagnetics and electrical resistivity are often used together to determine the boundaries of leachate plumes rather than the location of drums, although electromagnetics has been used for locating drums. Frequently a combination of geophysical survey methods is recommended. The results of any geophysical survey must be verified by sampling.

Determining Drum Integrity

Determining drum integrity is one of the most important and difficult aspects of the cleanup operation. Excavation and subsequent handling of unsound drums can result in spills and reactions which may jeopardize worker safety and public health.

The method generally used for determining drum integrity is to make a visual inspection of the drum surface for corrosion, leaks, swelling and missing bungs. This approach requires close contact with the drums, but is the only effective method available for determining drum integrity. A variety of non-destructive testing methods (i.e. eddy current, X-rays, ultrasonics) have been investigated as tools for determining integrity, but all have been found to have serious drawbacks or limitations. Use of ultrasonics or eddy current, for example, requires that the surface of the drum be relatively clean and free from chipping paint in order to get accurate readings. Drums which have been buried are frequently covered with soil, residue and chipping paint and cannot be safely and easily cleaned. Also, the integrity of the underside of the drum cannot be determined with these methods without lifting it.

The safety of workers in close contact with the drums must be protected by the use of appropriate safety gear and equipment. A variety of direct- reading, air monitoring equipment is available to determine radioactivity, oxygen levels, levels of explosives, and concentrations of toxic gases. This equipment generally has remote sensing capabilities and alarms to warn field personnel of impending danger as they approach the drum.

Excavation and On-Site Transfer of Drums

Some waste disposal sites may require certain pre-excavation activities to improve site access for heavy equipment, to drain a site to provide a more stable work surface, or to hydrologically isolate the site to prevent surface water and groundwater contamination.

Drum excavation is generally accomplished by using a combination of conventional excavation, lifting and loading equipment such as backhoes, front end loaders and bobcats, but with special equipment modifications or accessories adapted to hazardous waste sites. The most valuable piece of equipment for handling drums is the barrel grappler (Figure 1), which is a modified crawler-mounted backhoe with a rotating grapple head. The grapple attachment can rotate 360 degrees along a given plane and is hydraulically self adjusting in grip radius so that it can grab and lift various sizes of containers as well as containers which are slightly dented or bent.

Other attachments include nonsparking buckets to prevent explosions, morman bars to cover the teeth of backhoes to avoid puncturing drums, plexiglas safety shields for vehicle cabs, and drum lifting attachments such as nylon yokes and metal hoists.

Equipment used in the excavation and staging of drums must be suitable for digging, grabbing, lifting, loading and manipulating drums. Complete handling of a drum related problem usually requires a combination of equipment, particularly where the grappler is not available.

Where drums are found to be leaking or structurally unsound, the drum should be overpacked or the contents transferred to a new container in order to avoid spills or releases which could jeopardize worker safety. Where the grappler is available, it is generally not necessary for the worker to be in contact with drums and spills, thus rupture of unsound drums may not be a threat to worker safety in this instance.

Drum Opening, Sampling and Compatibility Testing

Once a drum has been excavated, a series of activities are undertaken which lead to final disposal or treatment of the wastes. The first step is to segregate the drums based on their contents (liquids, solids, gases, etc.). Next the drums are opened, sampled to determine compatibility and resealed. Drum opening and sampling should be performed in an isolated area in order to minimize the possibility of explosion and fires if drums spill or rupture. Drum opening tools include non-sparking hand tools, wrenches, deheaders, remotely operated plungers, debungers (Figure 2) and backhoe attached spikes (Figure 3). Where remotely operated methods are used, further protection should be provided by conducting the operation from behind a plexiglas shield. Measures should be taken to contain and mitigate spills which occur during drum opening. In general, remote drum opening is recommended where drum integrity is poor or the wastes are suspected of being highly toxic.

Compatibility testing should consist of rapid, on-site procedures for segregating incompatible wastes based on such factors as reactivity, solubility, presence of oxidizers, water content, etc. [4]. Drums containing similar wastes are consolidated in order to reduce the costs and time involved in cleanup and transportation.

Recontainerization or Consolidation

There are a number of options available for consolidating wastes or for recontainerizing them, if consolidation is not possible. In general, use of vacuum trucks is recommended where there are a minimum of 30 to 40 drums which can be consolidated.

Industrial strength vacuum units are available for consolidating both solids and liquids. Skid mounted vacuum units are available for areas inaccessible to trucks or where the number of drums to be consolidated is small. When using vacuum equipment, care must be taken to avoid incompatible waste reactions which can

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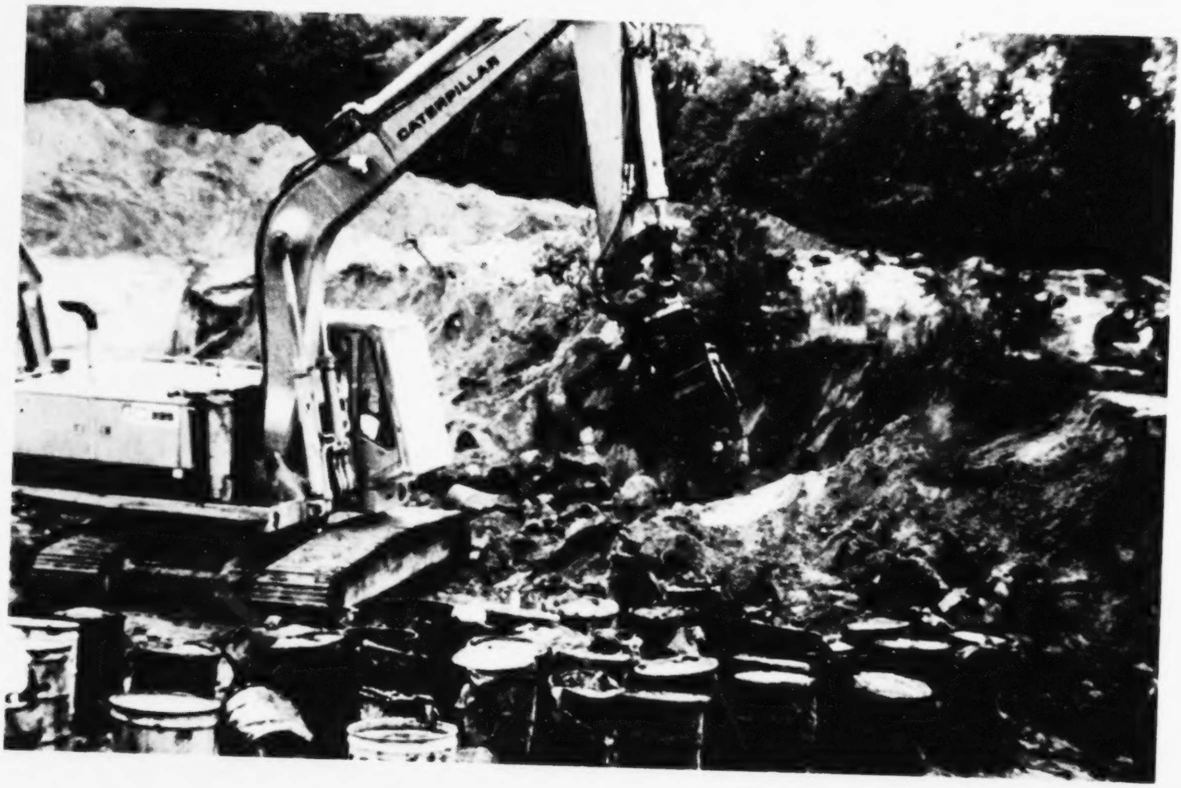

Figure 1. Barrel Grappler, Removing Drums from Pit Exavation
(Courtesy of O.H. Materials Co., Findlay, Ohio)

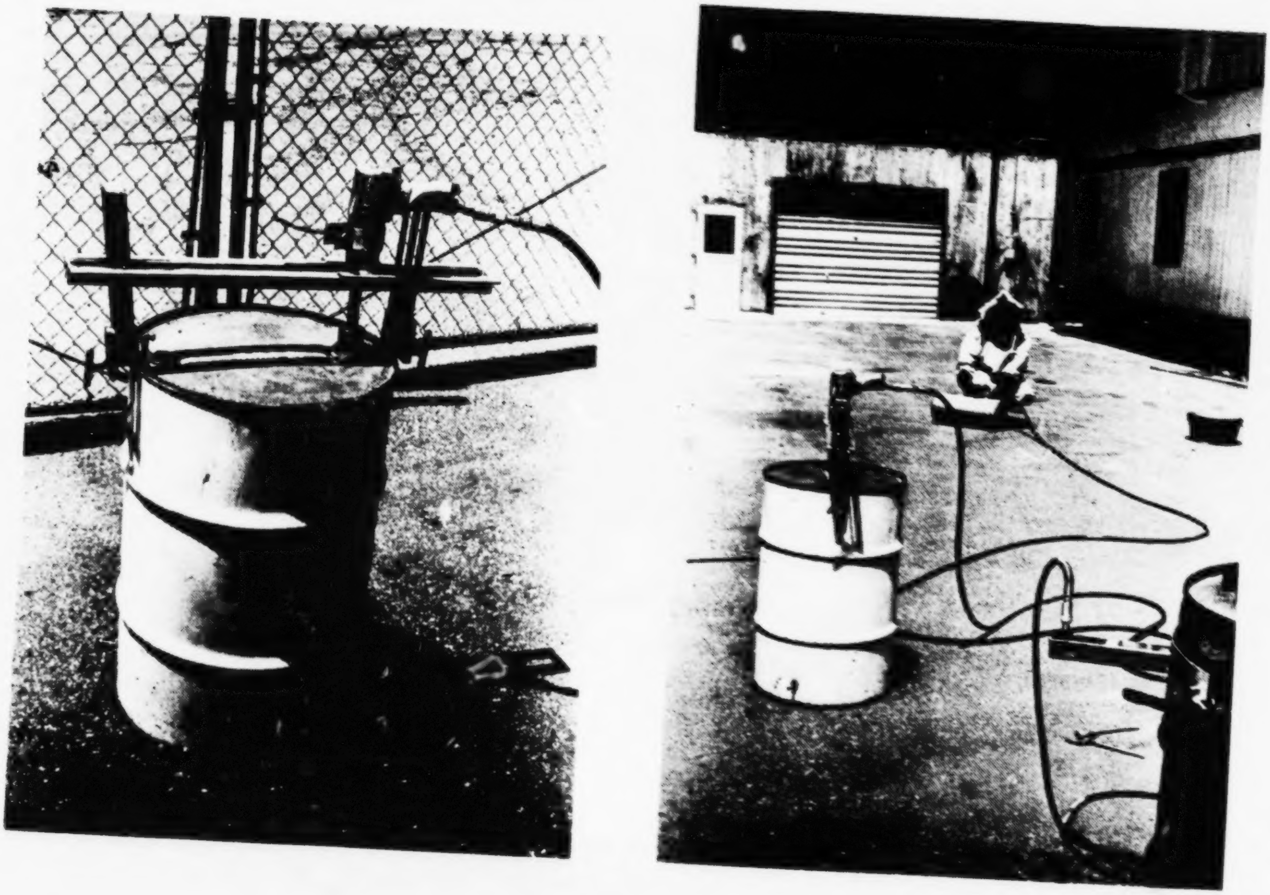

Figure 2. Pneumatic Bung Wrench: Attachment to Drum and Remote Operation Setup (3)

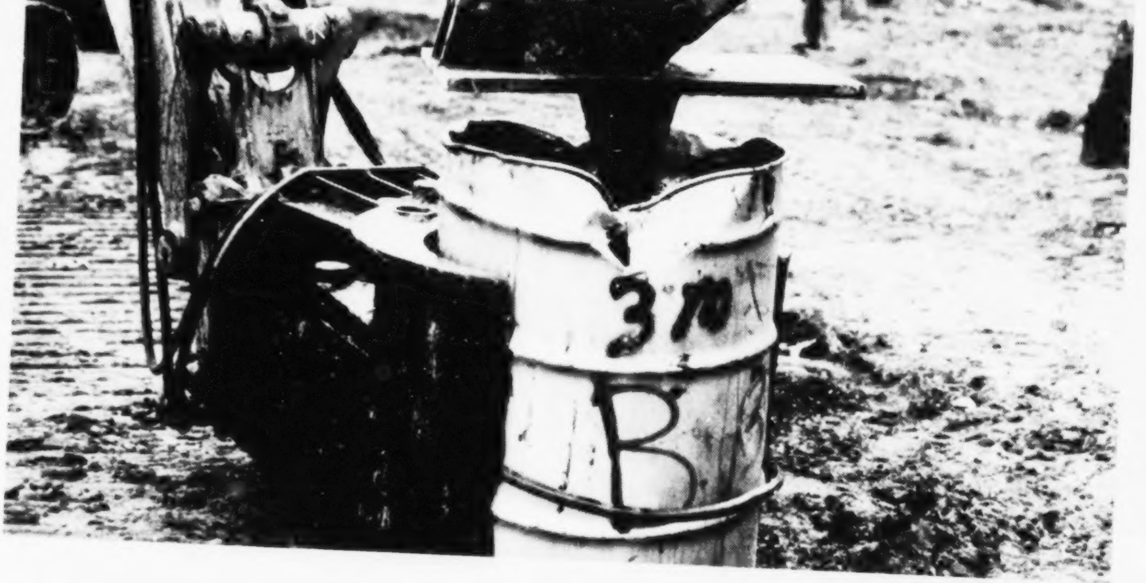

Figure 3. Backhoe Spike (Nonsparking) Puncturing Drum Held by Grappler
(Courtesy of O.H. Materials Co., Findlay, Ohio)

result in costly damage to the vacuum cylinder. Where incompatible waste reactions are possible, wastes should be allowed to react under carefully controlled conditions in a "compatibility" chamber prior to transfer to the vacuum truck.

If drums containing wastes cannot be consolidated because of incompatibility or where the number of drums is too small to make consolidation economical, they can be overpacked or their contents transferred to new drums for final disposal. This is frequently a more costly method of final disposal since drums and overpacks are bulky to transport. In weighing the relative costs of overpacking or consolidating wastes using vacuum equipment, the costs of decontaminating the vacuum equipment after use should also be included.

The final step in the cleanup process is decontamination. Equipment is rinsed in the contaminated work area and the contaminated rinse water is collected for treatment, if it is determined that it will contribute to groundwater or surface water contamination. Contaminated soils may be combined with sludges and solids and/or bulked, packed in drums, or treated on-site depending upon the volume of soils and the nature and concentration of contaminants. Empty drums are also decontaminated in some cases depending upon the nature of the wastes which were stored in them. This process may be facilitated by a drum shredder. If the number of empty drums is small, they can be crushed and overpacked. If the drums are not considered hazardous they can be crushed and loaded in bulk onto vans or flat-bed trucks. Decontamination of field workers, protective clothing and sampling equipment is essential part of the final cleanup process. Procedures for decontamination can be found in several publications including a Hazardous Waste Site Management Plan [4], and the EPA Safety Manual for Hazardous Waste Site Investigations [5].

Storage and Shipping

In some instances it may be necessary to store drums on-site temporarily until funds become available for final treatment/disposal or until a suitable disposal site is found. If drums are to remain on-site for a period of three or more months, then requirements for RCRA permitted facilities should be followed. These requirements include the following:

- Use of dikes or berms to enclose the storage area and to segregate incompatible waste types
- Installation of a base or liner which is impermeable to spills
- Sizing of each storage area (containing compatible wastes) so that it is adequate to contain at least 10 percent of the total waste volume in the event of a spill
- Design of the storage area so that drums are not in contact with rainwater or spills for more than 1 hour
- Weekly inspections.

Transportaion and final disposal of wastes from abandoned sites is governed by Department of Transportaion regulations as well as by state laws, disposal facility requirements, and in the case of highly toxic materials, by the Toxic Substances Control Act (TSCA).

CONCLUSIONS

The selection and implementation of equipment for drum handling is made on a case by case basis based upon the following considerations:

- Safety of the field workers
- Protection from environmental releases which could jeopardize public health
- Site-specific factors which effect equipment performance
- Costs.

There are a number of precautions which can be taken to protect field personnel. Many of these measures such as use of protective clothing, medical surveillance, communications, etc. apply to all waste investigations and cleanup operations and are not unique to drum handling. Other safety measures, such as use of non-sparking drum opening tools, or isolation of the drum opening operations are unique to drum handling.

In addition, precautions must be taken to minimize environmental releases. These include both measures for preventing spills, leaks and incompatible reactions as well as mitigative measures for containing and controlling spills or reactions which do occur.

Site specific variables such as accessibility of the site, the number of drums, site drainage, drum integrity, etc., effect equipment performance and safety, and must be considered in selecting and implementing drum handling methods. Table 3 summarizes the major site variables as they influence drum handling activities.

The final factor affecting the selection of equipment is costs. Because the number of drums, their contents and integrity are generally not known with any certainty at the outset of the cleanup operation, costs for cleanup can only be approximated. Costs can be minimized, however, by the selection of the most cost-effective contractor and equipment types and by close management of the cleanup operation.

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